Control of Rotor Side of DFIG with Intelligent Proportional Controller

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Abstract. A comparison between a classical Proportional Integral controller (PI) and a new intelligent Proportional controller (i-P), used for rotor current control a Doubly Fed Induction Generator (DFIG) based wind energy is presented. The DFIG is one of the most powerful generators with having many advantages compared to traditional generators. The power electronic interface is able to control the rotor currents for achieving a variable speed that is necessary for enhancing energy storage under variable winds. The objective is to find the technique that is able to provide the highest electricity production. Combining the effectiveness of a maximum power point tracking (MMPT), which is able to maximize the collected power from the turbine, an intelligent controller is introduced. The intelligent proportional controller is classified as one of model free control. The design of the controller is straightforward. In fact, only two signals are required: the input and the output. It is considered as an amelioration of the set of classical PID controllers (PI, PD and PID) by introducing a cancelling term in the classical version of control equation. The simulation results,with MATLAB and Simulink,shows its superiority to classical PI controller in power production and the same tracking performances with straightforward calibration process.

Keywords: Wind turbine · DFIG · MPPT · Model free control

1 Introduction

Previously, wind turbines have been operated at fixed speeds with classical induction machines to avoid the additional costs related to power electronic converters. However, due to its ability to operate over a wide speed range, the Doubly Fed Induction Generator (DFIG) has become the preferred generator for wind turbines. It improves the conversion efficiency and facilitates working with variable speed drive systems that have become dominant since smaller sized converters can be employed. For these reasons, the DFIG has replaced permanent magnet synchronous generators in wind turbine applications.

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Enhancing the power production is the priority in the DFIG concept. However, to ensure safe operation and optimal efficiency, a different strategy is necessary to control the rotor side converter of the wind turbine.. Some techniques perform the control in the current and not the voltage. For example, a fuzzy logic technique is applied as an alternative of the classical PI controller in the work presented by (Ayrir et al, 1). The active disturbance rejection control has shown its ability to reject online the parameter variations when it is applied to rotor currents (Chakib et al. 2).

Recently, new research are focused on the design of more effective controllers that are able to satisfy the requirements with low cost and easy implementation. The key element of the new generation of intelligent controllers is the annihilation of the use of a particle model. An intelligent-proportional i-P will be introduced in this chapter that has been applied in many fields and shown good performances and expectations according to Haddar et al. (3).

In this chapter, the mechanical and electrical components of a wind turbine system based on the DFIG is presented in Sect. 2 and 3. Then, the proposed controller is applied to the control of the rotor side converter in Sect. 4. In Sect. 5, the results are presented, where after the work is concluded.

2 Wind Turbine Model

The objective of a wind turbine is to transform the collected wind energy into mechanical power. The equation of aerodynamic power applied on a wind turbine rotor is written as follows (Chakib et al. 2):

$$P_{aer} = 0.5 C_p(\lambda, \beta)\rho\pi R^2 V^3 \tag{1}$$

where ρ is the air density (1.225 kg/m^3), V is the wind velocity (8 m/s) and R is the blade radius (42 m). The pitch angle is denoted β and the tip speed is denoted λ.

The power coefficient C_p is a characteristic that is dependent on the design of the wind turbine. For example the C_p expression used in this chapter is according to Abu-Rub H et al. (4).

$$C_p(\lambda, \beta) = C_1\left(\frac{C_2}{\lambda_i} - C_3\beta - C_4\right)e^{\left(\frac{-C_5}{\lambda_i}\right)} + C_6\lambda \tag{2}$$

with $\frac{1}{\lambda_i} = \frac{1}{\lambda+0.08\beta} - \frac{0.035}{\beta^3+1}$ and.

$C_1 = 0.5176,\ C_2 = 116,\ C_3 = 0.4,\ C_4 = 5,\ C_5 = 21,\ C_6 = 0.0068.$

The mechanical part (the gearbox system), is presented by a simplified model that is related to the electrical part (the generator) by this expression:

$$T_{mec} = T_m - T_{em} - f_v\Omega_m = \left(\frac{J_t}{N^2} + J_m\right)\frac{d\Omega_m}{dt} \tag{3}$$

where T_{mec}, T_m and T_{em} are the mechanical torque of generator, the torque of the turbine and the electromagnetic torque, respectively. $\left(\frac{J_t}{N^2} + J_m\right)$ is the total inertia of the system and Ω_m is the generator speed.

The three regions of the turbine operation are presented in Fig. 1. We are interested in the second region (highlighted in blue) when the wind velocity is greater than the cut-in speed, i.e. when the DFIG mechanism starts to work and produces electrical power. So, the MPPT is applied in this region to collect the maximum of power. In the last region, the pitch control will be activated that is not the subject of this chapter (see Fig. 1).

According to the fundamental equation of dynamics making it possible to determine the evolution of the mechanical speed from the total mechanical torque applied to the rotor, this speed can be adjusted to a reference. This is obtained by using an adequate control of the speed to have a reference electromagnetic torque as depicted in Fig. 2.

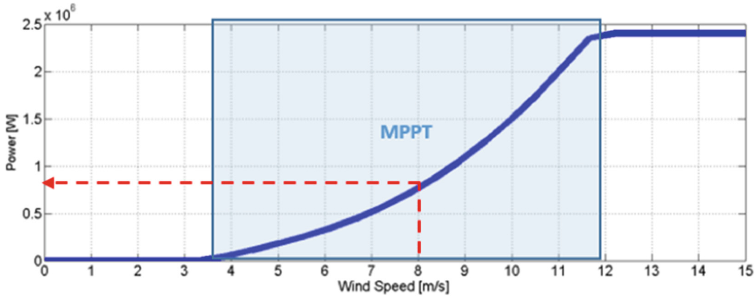

Fig. 1. The produced power under different wind speeds

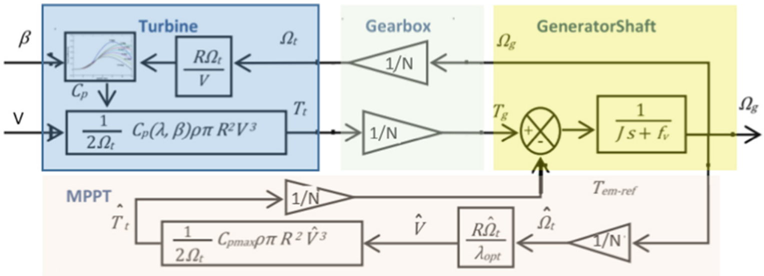

Fig. 2. MPPT control

3 DFIG Model

The current loop control can be represented as flowing:

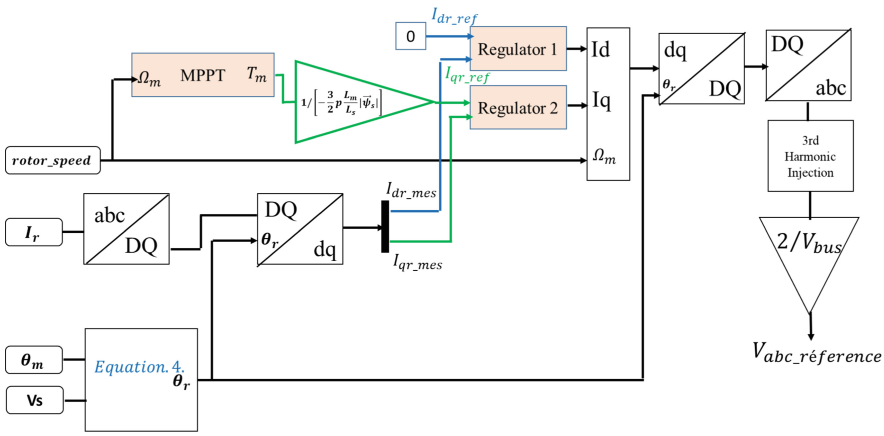

Fig. 3. The rotor current loop control

To get the rotor parameter θ_r used in the different transformation, we used this system of equation:

$$\begin{cases} V_S = V_\alpha + V_\beta \\ \theta = arctg\left(\frac{V_\beta}{V_\alpha}\right) \\ \theta_s = \theta - \frac{\pi}{2} \\ \theta_r = \theta_s - p.\theta_m \end{cases} \tag{4}$$

Two synchronous rotating reference frames (d and q) are used for vector control orientation in order to align the machine flux. According the previous assumption the rotor voltages equation can be represented as a function of the rotor current and stator flux $\overline{\psi}_s$ as following (Abu-Rub et al. 4):

$$\begin{cases} V_{qr} = U_{Vqr1} + \omega_r \sigma L_r I_{dr} + \omega_r \frac{L_m}{L_s} |\overline{\psi}_s| \\ V_{dr} = U_{Vdr1} - \omega_r \sigma L_r I_{qr} \end{cases} \tag{5}$$

The rotor current equations are:

$$\begin{cases} I_{qr} = \left[V_{qr} - \omega_r \sigma L_r I_{dr} + \omega_r \frac{L_m}{L_s} \left|\overline{\psi}_s\right|\right] \frac{1}{\sigma L_r s + R_r} \\ I_{dr} = \left[V_{dr} + \omega_r \sigma L_r I_{qr}\right] \frac{1}{\sigma L_r s + R_r} \end{cases} \tag{6}$$

The classical controller PI of rotor current at each frame:

$$\begin{cases} U_{Vq1}(t) = Kp_{iq}\left(I_{qr\_ref}(t) - I_{qr\_mes}(t)\right) + Ki_{iq} \int \left(I_{qr\_ref}(t) - I_{qr\_mes}(t)\right)dt \\ U_{Vd1} = Kp_{id}\left(I_{dr\_ref}(t) - I_{dr\_mes}(t)\right) + Ki_{id} \int \left(I_{dr\_ref}(t) - I_{dr\_mes}(t)\right)dt \end{cases} \tag{7}$$

The choice of gains parameters (Kp_{iq}, Kp_{id}, Ki_{iq} and Ki_{id}) can be obtained with the pole compensation method.

The (d-q) model of the DFIM is used for calculating the most useful magnitudes of the machine at the steady state part. The control process in the DFIG is designed according to precise requirements such as the reactive power Q_s, the electromagnetic torque T_{em} and ω_m the rotor electrical speed (Fig. 3).

In order to minimize the rotor current, the Q_s is set to zero. Hence the, I_{dref} is equal to zero. The torque T_{em} expression in the (d-q) frame can be simplified as follows:

$$T_{em} = -\frac{3}{2}p\frac{L_m}{L_s}\left|\vec{\psi}_s\right|I_{qr} \tag{8}$$

So, the reference of rotor current in the q frame is given by

$$I_{qr\_ref} = T_{em}/\left[-\frac{3}{2}p\frac{L_m}{L_s}\left|\vec{\psi}_s\right|\right] \tag{9}$$

The active power is given by the following expression:

$$P_m = T_{em}\Omega_m \tag{10}$$

4 Classical PI and Model Free Control

The model free control is a kind of intelligent controller based on an "ultra-local" model for the concept of controller equation. It is considered as an amelioration of the set of classical PID controllers (PI, PD and PID) by introducing a cancelling term in the classical version of control equation.

According to Fliess and Join (5), an equivalent to the PI controller is an intelligent proportional controller i-P which is given by:

$$\begin{cases} U_{Vq1}(t) = -\frac{[F(t)]_{est}}{\beta} + \frac{y_{iq}^{(1)}(t) - Kp_{iq}\left(I_{qr\_ref} - I_{qr\_mes}\right)}{\beta} \\ U_{Vd1}(t) = -\frac{[F(t)]_{est}}{\beta} + \frac{y_{id}^{(1)}(t) - Kp_{id}\left(I_{dr\_ref} - I_{dr\_mes}\right)}{\beta} \end{cases} \tag{11}$$

where $[F(t)]_{est}$ is a function that includes all kinds of unmodeled perturbations and its expression depends only the input and the output of the system:

$$[F(t)]_{est} = [y^{(1)}(t)]_{est} - \beta U_{V,i1}(t-1), i = d \; or \; q \tag{12}$$

β is a constant scaling parameter chosen by the operator.

In this chapter, a classical version of Model Free Control is used:

$$\begin{cases} [y_{iq}^{(1)}(t)]_{est} = \frac{dI_{qmes}(t)}{dt} \\ [y_{id}^{(1)}(t)]_{est} = \frac{dI_{dmes}(t)}{dt} \end{cases} \tag{13}$$

5 Simulation and Results

A constant wind speed equal to 8 m/s is used in the simulation. The parameters of DFIG are presented in Table 1.

$$\text{The PI controller parameters}\begin{cases} Kp_{id} = 2w_{ni}\sigma L_r - R_r \quad and \quad Ki_{id} = w_{ni}^2\sigma L_r \\ Kp_{iq} = Kp_{id}, Ki_{iq} = Ki_{id} \\ \tau_i = \sigma L_r/R_r, \tau_n = 0.05, w_{ni} = 100*(1/\tau_i) \end{cases}$$

$$\text{The i-P controller parameters}\begin{cases} Kp_{id} = 2w_{ni}\sigma L_r - R_r, \beta_d = 4.3\text{e - }08 \\ Kp_{iq} = Kp_{id}, \beta_q = 4.3\text{e - }08 \\ \tau_i = \sigma L_r/R_r, \tau_n = 0.05, w_{ni} = 100*(1/\tau_i) \end{cases}$$

Table 1. DFIG parameters.

Parameters (Units)	Value
f Stator frequency (Hz)	50
R_s Stator résistance (Ohm)	2.6e-3
R_r Rotor resistance refereed to stator (Ohm)	2.9e-3
p Pole pair	2
L_{si} Leakage inductance (H)	0.087e-3
L_m Magnetizing inductance (H)	2.5e-3
L_s Rotor inductance (H)	$L_m + L_{si}$
L_r Stator inductance (H)	$L_m + L_{si}$
V_{bus} DC bus voltage referred to stator (V)	325

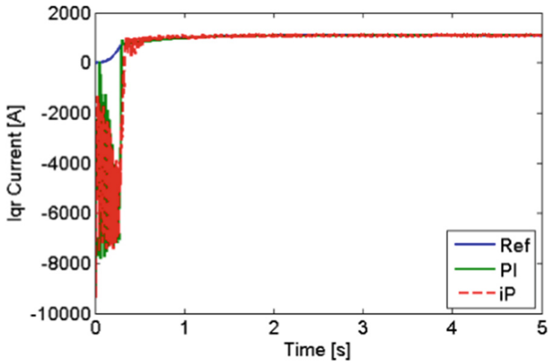

Fig. 4. The rotor current $\mathbf{I_{qr}}$ in the q frame

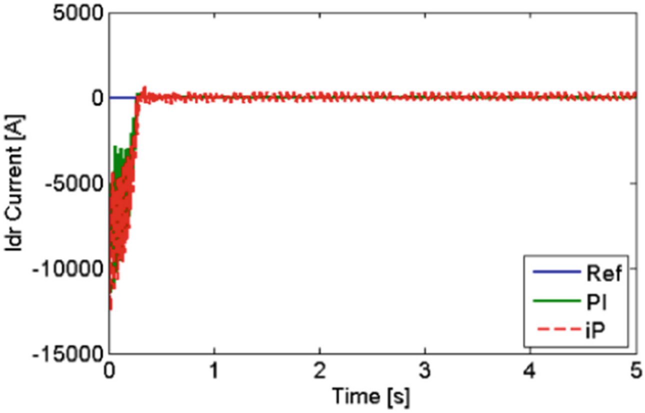

Fig. 5. The rotor current $\mathbf{I}_{dr}$ in the d frame

According to Figs. 4 and 5, the i-P controller is able to get the same tracking performance as the PI controller. The new term added in the control equation of the i-P controller has the propriety of an integral term. In fact, this term allows the elimination of the residual steady-state error, which happens with a pure proportional controller. Therefore, the advantage of the intelligent controller is its straightforward calibration compared to the PI controller.

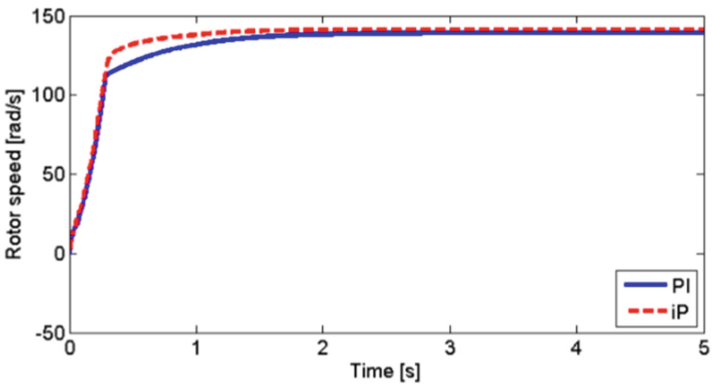

Fig. 6. The rotor speed $\mathbf{\Omega}_m$ with different controller

According to the rotor speed depicted in Fig. 6, the i-P controller improves and enhances the rotor speed from 139,3 rad/s to 141,3 rad/s. Figure 7 shows that the i-P controller allows the production of an electromagnetic torque, denoted Tem, that follows the required performance of the designer. The active power given by Eq. (10), is enhanced from 769400 W (with PI controller) to 799860 W (with i-P controller). This shows the superiority of the proposed i-P controller.

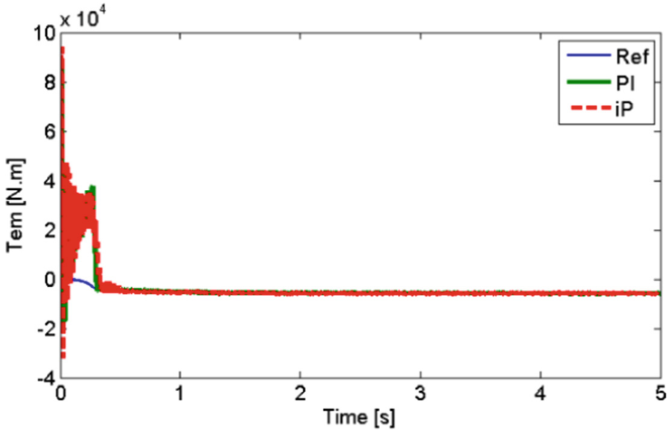

Fig. 7. The electromagnetic torque Tem

6 Conclusion

A comparative study was done between the classical PI controller and the intelligent proportional controller for the DFIG of a wind turbine model. The i-P controller is superior to enhance the active power level compared to PI. Moreover, it presents a better performance in tracking the references compared to the conventional PI and straightforward calibration. In future work, we will introduce the new version of Model Free Control and show its effectiveness to deal with the variation of machine parameters.

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Appendix

- dq to αβ transformation used in Eq. (4)

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} V_d \\ V_q \end{bmatrix}$$

- abc to DQ transformation

$$\begin{bmatrix} x_D \\ x_Q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix}$$

- abc to αβ transformation

$$\begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix}$$

- αβ to abc transformation

$$\begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix}$$

- DQ to dq transformation

$$\begin{bmatrix} x_d \\ x_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} x_D \\ x_Q \end{bmatrix}$$

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