Passivity based Controller for Doubly Fed Induction Generator with Wind Turbine

[1]ADNANI YOUNES, [2]AIT BASSOU AZIZ, [3]EL ALAMI NOUREDDINE, [4]EL ALAMI JAMILA

[1,2,4]LASTIMI,Superior School of Technology of Sale, EST-Sale
[3]LA2I,Department of Electrical Engineering, Mohammadia School Engineering
University Mohammed V of Rabat
Morocco
younes.adnani@gmail.com, aziz.bassou123@gmail.com

Abstract: - This paper studies the stability of a doubly fed induction generators for wind turbine, the system is closed loop and it is constructed around the port controlled Hamiltonian system with dissipation (PCHD). The control law is based on the passivity using the principle of interconnection and damping assignment (IDA PBC). Compared to a nonlinear system, the simulation results confirm the effectiveness of the proposed method.

Key-Words: - Doubly Fed Induction Generator (DFIG), Interconnection and Damping Assignment Passivity-Based Control (IDA-PBC), Wind Turbine (WT).

1 Introduction

Electricity is a concern of society. The depletion of reserves, environmental impact and rising fossil fuel prices indicate the need to diversify the generation system. In this context, wind power is a renewable energy that requires no fuel, creates no greenhouse gases, and does not produce toxic or radioactive waste. It is one of power generation sources to achieve lower cost to achieve the objectives that the European Union is set for 2020: 20 % renewable energy (wind and others) in overall consumption energy. Studies have shown that the global wind energy capacity will raise and thus increase global installed capacity. The growth observed in 2012 was driven specially by the United States and Europe[1].

Although primary experiments indicate that the maturity of the technology deployed in this domain might not be sufficient for the using of wind farms in large scale distant from shore, the rapid development of offshore wind energy is rapidly improving. Driven by customer demand and pressure to be very competitive in the market, wind power has become an area of great interest and concern. This same concern and interest extends to scientific research. Indeed, many research has focused on renewable energy in this case, wind power has increased considerably over the past long as it has good forecasts [1] [2]

In fact, research on wind energy systems has attracted much attention and achieved remarkable results. The Doubly Fed Induction Generation (DFIG) is a common configuration for large and variable speed wind turbines. Control problems of nonlinear systems wind turbines with DFIG are widely studied [1]. Several advanced design methods are used to design control for wind turbines based DFIG [3].

Also, passivity-based control (PBC) has flourished considerably. With its strengths application to several physical systems, it has considered as an important tool in nonlinear control research. Recently, the interconnection and damping assignment passivity based control (IDA-PBC) has become a flexible and appropriate method for the controllers design in nonlinear systems, by introducing a variety of tools to assign the interconnection and damping of internal energy.

[1] *HORS SERIE, le journal de l'éolien n°12-2013-Wind Energy Barometer-EUROBSERVER'S February 2013*

For designing a controller for DFIG, the stabilization of nonlinear systems shaping their energy function, has attracted more attention from many researchers for several years, we used a recent approach, which is the energy shaping controller design technique. [4],[5].

The new methodology, known as the Interconnection and Damping Assignment (IDA) approach, is based on energy shaping and passivation principles, which uses the passive properties of Port Hamiltonian system, this (IDA) technique is concerned with regulating the behavior of nonlinear systems assigning a desired port-controlled Hamiltonian structure to the closed-loop [4].

In this paper, we are interested in studying the problem of wind control of the DFIG through construction of the Hamiltonian energy function and get a Port Controlled Hamiltonian PCH model, which are a class of passive systems. Such system has been a real interest center for many researchers lately, in particular for stabilization objectives. The key of the procedure is transferred this function to another Hamiltonian function with dissipation (PCHD) using the feedback controller and shapes the function of energy to a PCHD. To apply the IDA-PBC, we propose to fix the structure of the energy function desired. Finally, the simulation which is compared to a nonlinear system has approved the efficiency of the proposed approach.

This paper is organized as follows: section two describes the IDA-PBC methodology. The proposed Doubly Fed Induction Generator control via IDA-PBC is detailed in Section 3; finally, section 4 deals with the implementation and experimental results.

2 The IDA PBC METHODOLOGY

The Interconnection and Damping Assignment passivity-based control (IDA-PBC) methodology is a feedback control design that intents to manipulate a port-Hamiltonian structure of the closed-loop system [6],[7].

IDA-PBC has found a large variety of applications. Numerous applications have been made to under actuated mechanical systems; A discrete-time counterpart of IDAPBC design for a class of Hamiltonian systems was developed in [8]. Furthermore, an Euler approximate model was used to have discrete-time control laws, which are implemented around the coordinate increment discrete gradient.

Moreover, the IDA-PBC control approach used under the actuated mechanical systems has been extended to integrate the open loop damping. The most important observation is that for a fixed closed loop inertia matrix, there is a sufficient and a necessary condition for the existence of a control redesign capable of managing the new damping terms [9] .

Recently, a non-linear controller based on the interconnection and damping assignment approach have been proposed to solve the problem of converters coordination of a fuel cell system involving a hydrogen fuel cell with super-capacitors for applications with high instantaneous dynamic power [10] Later, based on the IDA-PBC techniques extensions to the sampled-data context, a digital design was given for speed control of permanent magnet synchronous machines[11].

For a brief methodology explanation, let us consider the system [12]:

$$\dot{x} = f(x) + g(x)u \qquad (1)$$

And assume there are matrices $J_d(x) = -J_d^T(\text{x})$,

$R_d(x) = R_d^T(x) \geq 0$ and a function

$H_d(x): \Re^n \to \Re$ So that the closed loop system (1)

with control variable u

$$u = \left[g^T(x) g(x) \right]^{-1} \times$$
$$g^T(x) \left\{ \left[J_d(x) - R_d(x) \right] \nabla H_d - f(x) \right\}$$

Takes the PCH form

$$\dot{x} = \left[J_d(x) - R_d(x) \right] \nabla H_d \qquad (2)$$

$H_d(x)$ is such that $x^* = \arg\min_{x \in \Re^n} (H_d(x))$

With $x^* \in \Re^n$ the (locally) equilibrium to be stabilized. The system is asymptotically stable if, in addition, x^* is an isolated minimum of $H_d(x)$ and if the largest invariant remain under the closed-loop dynamics (2) contained in $\left\{x \in \Re^n / \left[\nabla H_d\right]^T R_d(x) \nabla H_d = 0\right\}$ equals x^*.

The stability of x^* is established noting that, along the trajectories of (2), we have $\dot{H}_d(x) = -\left[\nabla H_d\right]^T R_d(x) \nabla H_d \leq 0$

Hence, $H_d(x)$ is qualified as a Lyapunov function Asymptotic stability immediately follows invoking the La Salle's invariance principle (LaSalle,1960), see also in [13].Finally, to guarantee that the solutions remain bounded, we give the estimate of the field of attraction as the largest bounded, we give the estimate of the field of attraction s the largest bounded level set of $H_d(x)$.

3 DFIG control via PBC

In this section the considered model for the DFIG wind turbine is presented. First, the turbine model is introduced concentrating the attention to the existing relationship between the wind speed and the amount of wind power that can be captured by this device. The second and third parts are dedicated to presenting the construction of the PCH system and transformation of the obtained model to the PCH-D Port Controlled Hamiltonian with Dissipation system. In the last part a solution of equilibrium state is given.

3.1 Modeling DFIG wind turbine

A standard configuration of the DFIG-based wind turbine is shown in Figure 1, which is composed of the wind turbine, drive train, DFIG, controller and power grid.

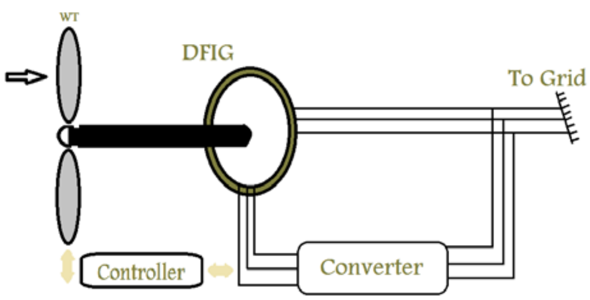


Figure 1: Basic Configuration of Wind Turbine with DFIG

In this paper, the model of the wind turbine with DFIG is a third-order model as proposed in [14]. Hereafter the equation's model:

$$\frac{ds}{dt} = \frac{P_s - P_m}{2H_{tot}} = \frac{-E_d^{'} i_{ds} - E_q^{'} i_{qs} - P_m}{2H_{tot}}$$

$$\frac{dE_q^{'}}{dt} = -s\omega_s E_d^{'} - \frac{1}{T_0^{'}}\left[E_q^{'} - \left(X_s - X_s^{'}\right) i_{ds}\right] + \omega_s \frac{L_m}{L_{rr}} v_{dr}$$

$$\frac{dE_d^{'}}{dt} = s\omega_s E_q^{'} - \frac{1}{T_0^{'}}\left[E_d^{'} - \left(X_s - X_s^{'}\right) i_{qs}\right] + \omega_s \frac{L_m}{L_{rr}} v_{qr} \quad (3)$$

Where $X_s = \omega_s L_{ss}, X_s^{'} = \omega_s\left(L_{ss} - \frac{L_m^2}{L_{rr}}\right), T_0^{'} = \frac{L_{rr}}{R_r}$

Notation

s	Rotor slip
H_{tot}	Total inertia constant of the turbine and the generator
P_s	Output active power of the stator of the DFIG
P_m	Mechanical power of the wind turbine
L_{ss}	Stator self-inductance
L_{rr}	Rotor self-inductance
L_m	Mutual inductance
ω_s	Synchronous angle speed
X_s , $X_s^{'}$	Stator reactance, Stator transient reactance
$E_d^{'}$, $E_q^{'}$	d ,q axis voltages behind the transient reactance
v_{dr} , v_{qr}	d , q axis rotor voltages

The model of the wind turbine with DFIG (3) is a system with two inputs v_{dr} and v_{qr} the states are $s, E_d^{'}$ and $E_q^{'}$.

The model of the wind turbine system with DFIG can be described by the following form:

$$\frac{d}{dt}\begin{pmatrix} s \\ E_q^{'} \\ E_d^{'} \end{pmatrix} = \begin{pmatrix} -\frac{i_{qs}}{2H_{tot}}E_q^{'} - \frac{i_{ds}}{2H_{tot}}E_d^{'} - \frac{P_m}{2H_{tot}} \\ -\frac{1}{T_0^{'}}E_q^{'} - s\omega_s E_d^{'} - \frac{i_{ds}}{T_0^{'}}\left(X_s - X_s^{'}\right) \\ s\omega_s E_q^{'} - \frac{E_d^{'}}{T_0^{'}} - \frac{i_{qs}}{T_0^{'}}\left(X_s - X_s^{'}\right) \end{pmatrix} + \begin{pmatrix} 0 & 0 \\ \omega_s \frac{L_m}{L_{rr}} & 0 \\ 0 & -\omega_s \frac{L_m}{L_{rr}} \end{pmatrix}\begin{pmatrix} v_{dr} \\ v_{qr} \end{pmatrix} \quad (4)$$

3.2 Port Controlled Hamiltonian system

The system (3) be able to rewritten in the PCH form

$$\frac{d}{dt}\begin{pmatrix} s \\ E_q^{'} \\ E_d^{'} \end{pmatrix} = \begin{pmatrix} 0 & -\frac{i_{qs}}{2H_{tot}} & -\frac{i_{ds}}{2H_{tot}} \\ 0 & -\frac{1}{T_0^{'}} & -s\omega_s \\ 0 & s\omega_s & -\frac{1}{T_0^{'}} \end{pmatrix}\nabla H$$

$$+\begin{pmatrix} 0 \\ \frac{i_{ds}}{T_0^{'}}\left(X_s - X_s^{'}\right) + \frac{P_m}{2T_0^{'}i_{qs}} + s\omega_s\frac{P_m}{2i_{ds}} \\ -\frac{i_{qs}}{T_0^{'}}\left(X_s - X_s^{'}\right) + \frac{P_m}{2T_0^{'}i_{ds}} - s\omega_s\frac{P_m}{2i_{qs}} \end{pmatrix} + \begin{pmatrix} 0 & 0 \\ \omega_s \frac{L_m}{L_{rr}} & 0 \\ 0 & -\omega_s \frac{L_m}{L_{rr}} \end{pmatrix}\begin{pmatrix} v_{dr} \\ v_{qr} \end{pmatrix} \quad (5)$$

Where $\nabla H = \left[s, E_q^{'} + \frac{P_m}{2i_{qs}}, E_d^{'} + \frac{P_m}{2i_{ds}} \right]$ (6)

Finally, the Hamiltonian energy function can be written as :

$$H = \frac{1}{2}s^2 + \frac{1}{2}(E_q^{'} + \frac{P_m}{2i_{qs}})^2 + \frac{1}{2}(E_d^{'} + \frac{P_m}{2i_{ds}})^2 \quad (7)$$

3.3 Port Controlled Hamiltonian with dissipation system

In this part, we give the Port Controlled Hamiltonian with Dissipation obtained from the PCD. The control law is given as follows:

$$u = \begin{bmatrix} v_{dr} \\ v_{qr} \end{bmatrix} = \xi + \psi = \begin{bmatrix} \xi_{dr} \\ \xi_{qr} \end{bmatrix} + \begin{bmatrix} \psi_{dr} \\ \psi_{qr} \end{bmatrix} \quad (8)$$

We design the feedback controller ξ , which takes the system satisfy PCH-D form

$$\xi = \begin{bmatrix} \xi_{dr} \\ \xi_{qr} \end{bmatrix}$$

$$= \begin{pmatrix} -\frac{L_{rr}}{\omega_s L_m}(\frac{i_{ds}}{T_0^{'}}\left(X_s - X_s^{'}\right) + \frac{P_m}{2T_0^{'}i_{qs}} + (\omega_s\frac{P_m}{2i_{ds}} - \frac{i_{qs}}{2H_{tot}})s) \\ \frac{L_{rr}}{\omega_s L_m}(-\frac{i_{qs}}{T_0^{'}}\left(X_s - X_s^{'}\right) + \frac{P_m}{2T_0^{'}i_{ds}} - (\omega_s\frac{P_m}{2i_{qs}} + \frac{i_{ds}}{2H_{tot}})s) \end{pmatrix} (9)$$

and replace (9) into (5).

The closed loop system will be a PCH system with dissipation PCH-D system:

$$\frac{d}{dt}\begin{pmatrix} s \\ E_q^{'} \\ E_d^{'} \end{pmatrix} = \begin{pmatrix} 0 & -\frac{i_{qs}}{2H_{tot}} & -\frac{i_{ds}}{2H_{tot}} \\ \frac{i_{qs}}{2H_{tot}} & -\frac{1}{T_0^{'}} & -s\omega_s \\ \frac{i_{ds}}{2H_{tot}} & s\omega_s & -\frac{1}{T_0^{'}} \end{pmatrix} \nabla H$$

$$+\begin{pmatrix} 0 & 0 \\ \omega_s \frac{L_m}{L_{rr}} & 0 \\ 0 & -\omega_s \frac{L_m}{L_{rr}} \end{pmatrix} \begin{pmatrix} v_{dr} \\ v_{qr} \end{pmatrix} \quad (10)$$

Where, $J = \begin{pmatrix} 0 & -\frac{i_{qs}}{2H_{tot}} & -\frac{i_{ds}}{2H_{tot}} \\ \frac{i_{qs}}{2H_{tot}} & 0 & -s\omega_s \\ \frac{i_{ds}}{2H_{tot}} & s\omega_s & 0 \end{pmatrix}$,

$$R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{1}{T_0^{'}} & 0 \\ 0 & 0 & \frac{1}{T_0^{'}} \end{pmatrix}$$

$$g = \begin{pmatrix} 0 & 0 \\ \omega_s \frac{L_m}{L_{rr}} & 0 \\ 0 & -\omega_s \frac{L_m}{L_{rr}} \end{pmatrix}; u = \begin{pmatrix} v_{dr} \\ v_{qr} \end{pmatrix}$$

A key step for the success of IDA-PBC methodology is the suit choice of the desired interconnexion and damping.

3.4 The desired equilibrium state

In this part, the main result of the paper is presented, namely, the controller expression.

The desired equilibrium state as

$$x^* = \left[x_1^*, x_2^*, x_3^* \right]^T$$

$$= \left[s^*, (E_q^{'} + \frac{P_m}{2i_{qs}})^*, (E_d^{'} + \frac{P_m}{2i_{ds}})^* \right]^T \quad (11)$$

So a control law is designed so that a dynamics of the closed loop system

$$\dot{x} = (J_d - R_d)\frac{\partial H_d(x)}{\partial x} \quad (12)$$

The main idea of IDA-PBC is to assign to the closed-loop a desired storage function via the modification of the interconnection and dissipation matrices. We use IDA PBC controller synthesis to compute the control law.

For an application of IDA-PBC, we propose to fix the structure of the desired energy function

$$H_d(x) = \frac{1}{2}\left[(x_1 - x_1^*)^2 + (x_2 - x_2^*)^2 + (x_3 - x_3^*)^2 \right] (13)$$

$$J_d - R_d = \begin{pmatrix} 0 & -j_{12} & -j_{13} \\ j_{12} & -r_2 & -j_{23} \\ j_{13} & j_{23} & -r_3 \end{pmatrix}$$

With $r_i \succ 0$, j_{ij} represents interconnections and damping parameters respectively.

J_d , R_d represents respectively the desired interconnexion and damping matrices

$$(J - R)\frac{\partial H(x)}{\partial x} + g = (J_d - R_d)\frac{\partial H_d(x)}{\partial x} \quad (14)$$

Is satisfied, where

$J_d(x) = J(x) + J_a(x) = -(J(x) + J_a(x))^T$ and

$R_d(x) = R(x) + R_a(x) = (\mathrm{R}(x) + R_a(x))^T \geq 0$

for the procedure for the controller defining, we fix the interconnexion and damping matrices as $J_d(x) = J(x,u)$ and $R_d(x) = R(x)$ i.e., $J_a(x) = 0$ and $R_a(x) = 0$.

Let $\xi(x) = \frac{\partial H_a(x)}{\partial x} = \left(\xi_1, \xi_2, \xi_3\right)^T$ .Equation (14) simplified $-\left[J - R\right]\frac{\partial H_a}{\partial x} + gu = 0$ (15)

Equation (15) can be solved for the controls

$$-j_{12}\tilde{x}_2 - j_{13}\tilde{x}_3 + x_2\frac{i_{qs}}{2H_{tot}} + x_3\frac{i_{ds}}{2H_{tot}} = 0 \quad (16)$$

$$v_{dr} = \frac{1}{\gamma}\left[j_{12}\tilde{x}_1 - r_2\tilde{x}_2 - j_{23}\tilde{x}_3 - x_1\frac{i_{qs}}{2H_{tot}} + \frac{x_2}{T_0^{'}} + s\omega_s x_3\right] \quad (17)$$

$$v_{qr} = \frac{1}{\gamma}\left[j_{13}\tilde{x}_1 - r_3\tilde{x}_3 - j_{23}\tilde{x}_3 - x_1\frac{i_{ds}}{2H_{tot}} - \frac{x_3}{T_0^{'}} + s\omega_s x_2\right] \quad (18)$$

with $\gamma = \omega_s \frac{L_{rr}}{L_m}$

Where x^* is the desired equilibrium point, and $j_{12}, j_{13}, j_{23}, r_2, r_3$ are design parameters, with $r_2, r_3 \succ 0$ and $j_{ij}x \in \mathbb{R}$; where $x_2^* = x_3^* = 0$, to find the solution of equation (16),we make a simplification taking $j_{12} = \frac{i_{ds}}{2H_{tot}}$ and $j_{13} = \frac{i_{qs}}{2H_{tot}}$

Thus, the controller expression is given as follow:

$$v_{dr} = \frac{1}{\gamma}\left[\frac{i_{ds}}{2H_{tot}}\tilde{x}_1 - x_1\frac{i_{qs}}{2H_{tot}} + \frac{x_2}{T_0^{'}} + s\omega_s x_3\right] - r_2\tilde{x}_2 - j_{23}\tilde{x}_3$$

$$v_{qr} = \frac{1}{\gamma}\left[\frac{i_{qs}}{2H_{tot}}\tilde{x}_1 - x_1\frac{i_{ds}}{2H_{tot}} - \frac{x_3}{T_0^{'}} + s\omega_s x_2\right] - \tilde{x}_3(r_3 + j_{23}) \quad (19)$$

Elements of the reference x^* are chosen according to control objectives.

The gradient of $H_d(x)$ at x^* : $\left.\frac{\partial H_d(x)}{\partial x}\right|_{x=x^*} = 0$ and

The Hessian $\frac{\partial^2 H_d}{\partial x^2}(x) \succ 0$ is positive definite. This ensures global asymptotic stability of x^* with Lyapunov function $H_d(x)$.

4 Simulations

This section aims to provide a few simulation results. Thus, we implement a numerical application of the entire system controlled via the IDA-PBC controllers. Thus, in order to illustrate the effectiveness of design result, the computer simulation was performed to evaluate the performance of system (3) with parameters of the wind turbine (WT) with DFIG is given as follow:

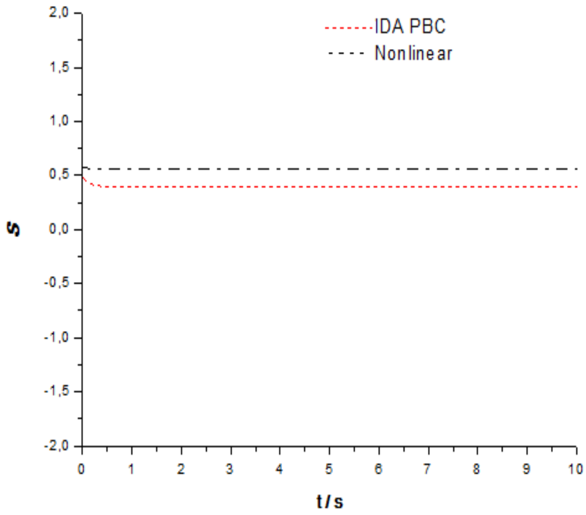
Para.	Value	Units
H_{tot}	3	s
L_m	2.9	pu
L_s	0.171	pu
L_r	0.156	pu
R_s	0.00706	pu
R_r	03005	pu
$L_{ss}=L_s+L_m$	3.071	pu
$L_{rr}=L_r+L_m$	3.056	pu

TABLE 1: SYSTEM PARAMETERS

The simulation results of the IDA passivity based control are compared with those of the nonlinear controller in[14] , which is for the same system model (3).

The dynamic response curves of three state variables ($s, E_q^{'}, E_d^{'}$) under two controllers is given in Figure.2-4.

From the figures, it is shown that the closed-loop systems remain stable and the states converge to the equilibrium point quickly under both of the controllers. Therefore, both of them are effective for DFIG-based wind turbine system. However, according to the convergence time, the nonlinear control in [14] seems be quicker than the IDA PBC proposed in this paper.



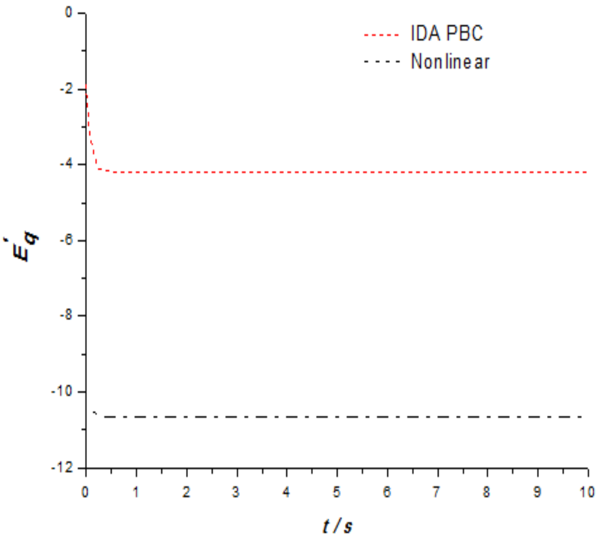


Figure 3: q-axis voltages $E_q^{'}$

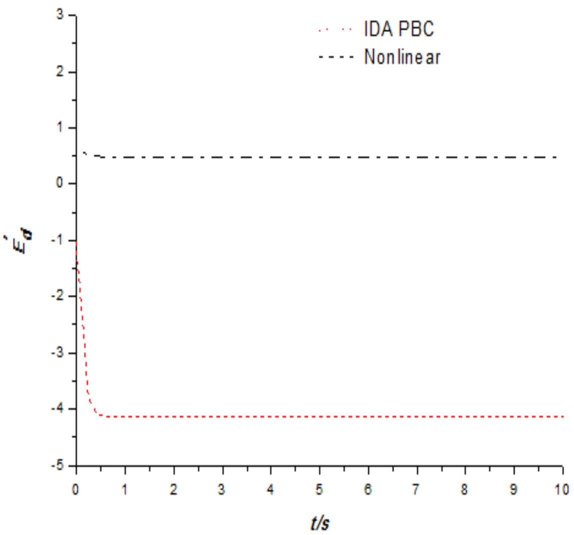


Figure 4: d-axis voltages $E_d^{'}$

In summary, according to the simulation results analysis, we can conclude that the IDA with DFIG which guarantees the stability of wind turbine remains better than the nonlinear controller.

4 Conclusion

In this paper, we have proposed an IDA PBC for DFIG-based wind turbines based on Hamiltonian energy theory. Firstly, a port-controlled Hamiltonian (PCH) model is established. The key procedure in using the energy function method is to transform the nonlinear system into a port controlled Hamiltonian system with dissipation (PCH-D). Secondly, with the energy shaping theory of interconnection and damping assignment passivity based control IDA PBC techniques, the feedback control theory for the system design is given. Finally, the equilibrium point of the system is obtained, and the stability of equilibrium point is analyzed. Result simulation The closed-loop system is asymptotically stable, during the energy-based design energy function and transformation into the port-controlled Hamiltonian system. The IDA PBC technique provides an effective design means compared to the nonlinear control design.

References:

[1] S. Muller, "Doubly fed induction generator systems for wind turbines," *Ind. Appl. …*, vol. 8, pp. 26–33, 2002.

[2] A. Petersson, *Analysis, modeling and control of doubly-fed induction generators for wind turbines.* 2005.

[3] G. Tapia, "Modeling and control of a wind turbine driven doubly fed induction generator," *IEEE Trans. Energy Convers.*, pp. 194–204, 2003.

[4] R. Ortega, A. Van der Schaft, B. Maschke, and G. Escobar, "Interconnection and damping assignment passivity-based control of port-controlled Hamiltonian systems," *Automatica*, vol. 38, no. 4, pp. 585–596, 2002.

[5] D. A. Dirksz, J. M. A. Scherpen, and R. Ortega, "Interconnection and Damping Assignment Passivity-Based Control for port-Hamiltonian mechanical systems with only position measurements," in *Proceedings of the IEEE Conference on Decision and Control*, 2008, pp. 4957–4962.

[6] R. Ortega, A. Loria, P. Nicklasson, and H. Sira-Ramirez, *Passivity-based control of Euler-Lagrange systems, 1998*. Springer London, 1998.

[7] R. Ortega, A. Loria, R. Kelly, and L. Praly, "On passivity-based output feedback global stabilization of Euler-Lagrange systems," *Proc. 1994 33rd IEEE Conf. Decis. Control*, vol. 1, 1994.

[8] D. S. Laila and a. Astolfi, "Discrete-time IDA-PBC design for underactuated Hamiltonian control systems," *2006 Am. Control Conf.*, p. 6 pp., 2006.

[9] F. Gómez-Estern and a. J. Van der Schaft, "Physical Damping in IDA-PBC Controlled Underactuated Mechanical Systems," *Eur. J. Control*, vol. 10, no. 5, pp. 451–468, Jan. 2004.

[10] M. Hilairet, M. Ghanes, O. Béthoux, V. Tanasa, J.-P. Barbot, and D. Normand-Cyrot, "A passivity-based controller for coordination of converters in a fuel cell system," *Control Eng. Pract.*, vol. 21, no. 8, pp. 1097–1109, Aug. 2013.

[11] M. Khanchoul, M. Hilairet, and D. Normand-Cyrot, "A Passivity-Based Controller Under low sampling for speed control of PMSM," *Control Eng. Pract.*, vol. 26, pp. 20–27, 2014.

[12] R. Ortega and E. García-Canseco, "Interconnection and Damping Assignment Passivity-Based Control: A Survey," *European Journal of Control*, vol. 10, no. 5. pp. 432–450, 2004.

[13] H. K. Khalil, "Nonlinear systems, 3rd," *New Jewsey, Prentice Hall*, vol. 9, 2002.

[14] F. Wu and X. Zhang, "Decentralized nonlinear control of wind turbine with doubly fed induction generator," *Power Syst. IEEE …*, vol. 23, no. 2, pp. 613–621, 2008.