DFIG with Adaptive Control using B-spline Neural Networks

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Abstract: - The doubly fed induction generator enables better use of wind energy, but it is necessary to have an adequate control scheme that achieves optimum performance in steady state and transient condition. The paper aim is to show that using B-spline neural networks,the electrical grid including wind energy systemscan achieve satisfactory operation. The control structure is based on a back to backarrangement where the interest variables are regulated by PI linear controllers. However, to deal with the nonlinear and uncertain system conditionswe proposed that the control parameters are updated online.The main task is that the power converters operation adapt by itself during the grid changes. The basic problem consists of tuning the PI controllers simultaneously when the system and load are subjected to disturbances. The applicability of the proposal is demonstrated by simulation in a three-node grid, where one end is an infinite bus and the other connects the wind system, between them there are two transmission lines. Results exhibit that the proposed controllers' tuning is comparable to that obtained by a conventional design, without requiring a detailed model.

Key-Words: -Adaptive controllers, DFIG, electronic devices.

1 Introduction

Currently, electric grids have limitations of power flows transfer from conventional generation plants to electricity consumers because the system could operate at the stability limits. But, with the technology advanced in power electronic devices is possible to include several generation systems based on alternative sources near to loads. However, an important part of the successful depends on power electronic devices control.

Electrical power generation with wind and solar as power sources may be considered of the most promising renewable energy sources, but the control schemes are an important issue [1]. There are extensive frameworks of various electrical machines types and controls algorithms that have been developed for wind generator applications [2-3].

Among the schemes of wind energy conversion systems (WECS), the induction and permanent magnet synchronous machines are seen as promising elements for energy conversion. In all cases back to back (BTB) arrangement based on power electronics is required to get benefits [3-5].

BTB structure is formed by two identical voltage source converters (VSC) connected by a common dc-link. This topology presents several advantages in terms of power processing and allows bidirectional power flow with quasi-sinusoidal currents. The load can be active, passive or even another network, in such case achieve a unity power factor is possible if it is required. The dc-link in the middle provides decoupling between both converters; as a result, they could be driven independently. Therefore, it is possible to have a fast and independent control of active and reactive power for both converters and improve the system operation [6]. To attain simultaneously these benefits is important to explore control strategies, which allow obtaining the desired regulation.

Several studies that examine WECS have been developed and make different proposals about what should be the control scheme and the tuning methodology [4-5, 7-8]. [1] presents a review of numerous control strategies adapted for WECS application, thus establishing that there is great interest in getting the best algorithm for secure and reliable system operation. Some of them considered

PI controllers for control schemes in BTB converters [4, 9]. The linear models design can exhibit some deficiencies for instance the controller tuning is guaranteed around an equilibrium point, when the system is subjected to changes in its operating condition or structure the performance is diminished. There are also several proposed adaptive controls to determine the controllers [8,10]. In [10] adaptive PID gains for each controller to achieve satisfactory performance is proposed.

In this paper a B-spline neural network (BSNN) is employed for two main tasks one for PI simultaneous tuning, taking care of a key feature: the proposed controller must be able to enhance the system performance; the second the online parameters updated can be possible. The strategy is proposed to update conventional PI parameters for currently operating in power converters that were tuned time ago. The main idea is to re-tune basically the control gains through an on-line procedure. After that, the same controllers' devices may continue working properly.

2 Problem Formulation

There is great interest that alternative generation systems should be included in conventional electrical grids, however, it is also true that further studies are required to fully justifying the feasibility and reliability of new source structures.From a design point of view one of the main issues is seeking for a safe and reliable operation under transient and steady state conditions. Therefore, before the implementation a comprehensive analysis using simulation is required, which allows determining system performance. Thus,it is important to present some subsystems mathematical models that are involved in WECS based on double fed induction generator (DFIG), Fig. 1.

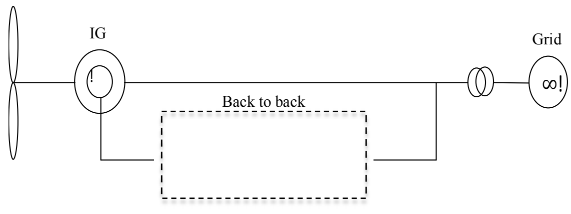

Fig. 1. WECS based on DFIG.

2.1 Back to Back model

The BTBscheme is formed by two shared VSC with a common DC bus. Both can operate as a rectifier or inverter depending on the power flow direction and the operation is complementary.

The VSC shown in Fig. 2 is the three-phase diagram with three-wire connected to the AC load represented by an equivalent Thevenin circuit by means a coupling transformer inductance and resistance (L_T, R_T). The DC converter terminal is connected to a shunt capacitance, C_{dc}. The three-phase AC side VSC voltage balancing equation is:

$$L_S\frac{d\mathbf{I}_{abc}}{dt}+R_S\mathbf{I}_{abc}+L_T\frac{d\mathbf{I}_{abc}}{dt}+R_T\mathbf{I}_{abc}=\mathbf{V}_{Sabc}-\mathbf{V}_{Tabc} \quad (1)$$

where$\mathbf{I}_{abc}=[I_a \quad I_b \quad I_c]^T$; $\mathbf{V}_{Sabc}=[V_{Sa} \quad V_{Sb} \quad V_{Sc}]^T$;$\mathbf{V}_{Tabc}=[V_{Ta} \quad V_{Tb} \quad V_{Tc}]^T$ are the three phase current, source and terminal voltage vector, respectively.The rms amplitude $V_{Tm}=m_0V_{dc}$ is obtained by the PWM modulation index $(0<m_0<1)$. The frequency ω and phase angle $\emptyset_T$ are PWM voltage source converter controllable variables.

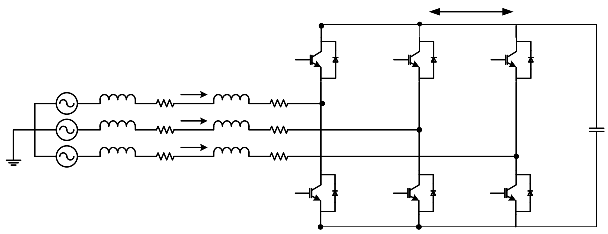

Fig. 2. Voltage source converter model.

The DC-side voltage dynamic expression is deduced based on power balance between the AC and DC-side as,

$$v_{dc}(t)i_{dc}(t)=P(t)-P_L(t) \quad (2)$$

where$P(t)$ is the instantaneous real power at point of common coupling; $P_L(t)$ includes the total power loss; and $P_{dc}=v_{dc}i_{dc}$ is the transferred power from the DC side to the load. The DC current is:

$$C_{dc}\frac{dv_{dc}}{dt}=i_{dc}-\frac{v_{dc}}{R_{dc}} \quad (3)$$

Both VSC's have the same dynamic model, only one act as a rectifier and another as inverter.

2.2 Control Scheme

The control objectives for the BTB operation are set depending on the application. In this paper for DFIG we are seeking to maintain the dc voltage at a constant value and the wind system operation with a unity power factor, which means that the reactive power flow towards the gridmust bezero.

2.2.1 Source side converter control

The source side converter objective is to keep the dc-link voltage constant. The vector control method is used with a reference frame oriented along vector position, enabling independent control of the active and reactive power flowing between the source and the converter [11]. The PWM signals are obtained by current regulated scheme, with $d-axis$ current used to manipulate the DC voltage and the $q-axis$ current component to regulate the reactive power. The voltage equations in synchronously rotating $dq-axis$reference frame are [12]:

$$v_{cd} = Ri_{cd} + L_{choke}\frac{di_{cd}}{dt} - \omega_e L_{choke} i_{cq} + v_{cd1} \tag{4}$$

$$v_{cq} = Ri_{cq} + L_{choke}\frac{di_{cq}}{dt} + \omega_e L_{choke} i_{cd} + v_{cq1} \tag{5}$$

The grid voltage angular position is calculated as

$$\theta_e = \int \omega_e dt = \tan^{-1}\frac{v_{c\beta}}{v_{c\alpha}} \tag{6}$$

where$v_{c\alpha}$ and $v_{c\beta}$ are the converter source side voltage components in stationary frame. The $d-axis$ of the reference frame is aligned with the grid voltage angular position θ_e. Since the grid voltage amplitude is constant, v_{cd} is constant and $v_{cq}=0$. The active and reactive power will be proportional to i_{cd} and i_{cq}, respectively.Thus, the control scheme utilizes a decoupled currents, i_{cd} and i_{cq}. The component i_{cd} is derived from the DCvoltage error through a PI controller. i_{cq}determines the displacement factor in the inductors supply-side. The reference values for the grid-side converter v_{d1}^* and v_{q1}^* are established with a PI controller.

$$v_{cd}^* = -v_{cd}' + \left(\omega_e L_{choke} i_{cq} + v_d\right) \tag{7}$$

$$v_{cq}^* = -v_{cq}' - \left(\omega_e L_{choke} i_{cd}\right) \tag{8}$$

2.2.2 Rotor side converter control

The rotor-side converter provides the excitation for the rotor. With this VSC is possible to control the torque, hence the induction generator (IG) speed and also the power factor at the stator terminals. The rotor-side converter provides a varying excitation frequency depending on the wind speed conditions. The IG is controlled in a synchronously rotating $dq0$, with the $d-axis$ oriented along the stator-flux vector position. This is called stator-flux orientation vector control. In this way, a decoupled control between the electrical torque and the rotor excitation current is obtained [11]. Consequently, the active power and reactive power are controlled independently from each other. To describe the control scheme, the induction machine model is introduced. Using the motor convention in a static stator-oriented reference frame without saturation, the voltage vector equations are [12],

$$\vec{v}_s = R_s\vec{i}_s + \frac{d\vec{\psi}_s}{dt} \tag{9}$$

$$\vec{v}_r = R_r\vec{i}_r + \frac{d\vec{\psi}_r}{dt} - j\omega\vec{\psi}_r \tag{10}$$

where$\vec{v}_s$ is the stator voltage imposed by the grid. The rotor voltage $\vec{v}_r$ is controlled by the rotor-side converter and used to perform generator control. Under stator-flux orientation, in $dqaxis$ component form, the stator flux equations are:

$$\begin{cases} \psi_{sd} = L_s i_{sd} + L_m i_{rd} \\ \psi_{sq} = 0 \end{cases} \tag{11}$$

Defining leakage factor $\sigma = 1 - L_m^2/L_sL_r$ and equivalent inductance as $L_0 = L_m^2/L_s$, the rotor voltage and flux equations are (scaled to be numerically equal to the ac per-phase values):

$$\begin{cases} v_{rd} = R_r i_{rd} + \sigma L_r \dfrac{di_{rd}}{dt} - \omega_{slip}\sigma L_r i_{rq} \\ v_{rq} = R_r i_{rq} + \sigma L_r \dfrac{di_{rq}}{dt} + \omega_{slip}\left(L_0 i_{ms} + \sigma L_r i_{rd}\right) \end{cases} \tag{12}$$

$$\begin{cases} \psi_{rd} = \dfrac{L_m^2}{L_s} i_{ms} + \sigma L_r i_{rd} \\ \psi_{rq} = \sigma L_r i_{rq} \end{cases} \tag{13}$$

where the slip angular speed is $\omega_{slip} = \omega_s - \omega_r$.

$$\begin{cases} v_{rd}' = R_r i_{rd} + \sigma L_r \dfrac{di_{rd}}{dt} \\ v_{rq}' = R_r i_{rq} + \sigma L_r \dfrac{di_{rq}}{dt} \end{cases} \tag{14}$$

To ensure good tracking of the rotor $dq-axis$ currents, compensation terms are added to v_{rd}' y v_{rq}' to obtained the reference voltages v_{rd}^* and v_{rq}^* according to

$$\begin{cases} v_{rd}^* = v_{rd}' - \omega_{slip}\sigma L_r i_{rq} \\ v_{rq}^* = v_{rqr}' + \omega_{slip}(L_m i_{ms} + \sigma L_r i_{rd}) \end{cases} \tag{15}$$

The electromagnetic torque is

$$T_e = -\frac{3}{2}p\,\mathrm{Im}\{\vec{\psi}_s\vec{i}_r^*\} = -\frac{3}{2}pL_0 i_{ms} i_{rq} \tag{16}$$

where$\mathrm{i}_{\mathrm{rq}}^*$

$$i_{rq}^* = -\frac{2T_e^*}{3pL_0 i_{ms}} = -\frac{2T_e^*}{3p\psi_s} \tag{17}$$

The reference values for the rotor-side converter v_{rd}^{*} and v_{rq}^{*} are established with a PI controller, respectively. Also a PI controller for i_{rq}^{*} is needed.

One important issue is how we can select the best PI parameters for the seven linear controllers, three for grid side and others for rotor side, thus fourteen parameters are required. Usually, this procedure is carried out based on linear analysis.

3 Problem Solution

3.1 Tuning proposed

The proposed can be achieved adding a B-spline neural network to update all gains in only five PI controllers, rotor and source sides. Thus, k_p and k_i are updated from a B-spline neural network at every sampled time. With this purpose, tenBSNNare assembled in the control scheme.The B-spline neural networks are a particular case of neural networks that allow to control and model systems adaptively, with the option of carrying out such tasks on-line, and taking into account the power grid non-linearities.Through BSNN there is the possibility to bound the input space by the basis functions definition. Therefore, not all the weights have to be calculated each sample time, thus reducing the computational effort and time.

The BSNN's output can be described by [13],

$$y = \mathbf{a}^T \mathbf{w} \qquad (18)$$

$$\mathbf{w} = [w_1 \quad w_2 \dots \quad w_p]^T; \quad \mathbf{a} = [a_1 \quad a_2 \dots \quad a_\rho]^T (19)$$

wherew_i and a_i are the i-th weight and the i-th BSNN basis function output, respectively; ρ is the number of weighting factors.

In this paper it is proposed that k_p and k_i be adapted through one B-spline neural network, respectively, for each voltage source converter. The error signals are the same of PI controllers. Then the dynamic control parameters for back to back system can be described as follows:

$$K_x = NN_m\left(e_x, w_\rho\right) \qquad (20)$$

whereNN_m denotes the B-spline network which is used to calculate k_p and k_i; w_ρ is the corresponding weighting factor; $m = 1,2,3$ number of PI controllers. Fig. 3 depicts a scheme of the proposed B-spline neural network.

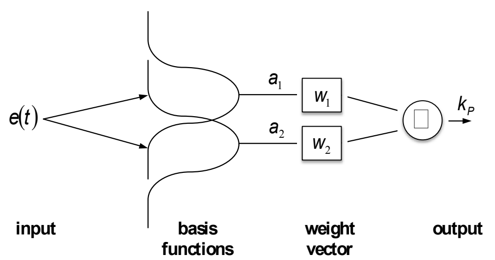

Fig. 3. Proposed BSNN for adapting control parameters.

The appropriate design requires the following a-priori information: the bounded values of e_x, the size, shape, and overlap definition of the basis function. Likewise, with this information the BSNN estimates the optimal weights' value. The neural network adaptive parameters, (18)-(20) are created by univariate basis functions of order 3, considering that e_x are bounded within [-12, 12]. In this paper, the BSNN is trained on-line using the following error correction instantaneous learning rule [13],

$$w_i(t) = w_i(t-1) + \frac{\eta e_i(t)}{\|\mathbf{a}(t)\|_2^2} a_i(t) (21)$$

whereη is the learning rate and $e_i(t)$ is the instantaneous output error.

Respect to the learning rate, it takes as initial value one point within the interval [0, 2] due to stability purposes. This value is adjusted by trial-and-error. If η is set close to 0, the training becomes slow. On the contrary, if it is large, oscillations may occur. In this application, it settles down in 0.051 for k_p, and 0.0016 for k_i.The BSNN training process is carried out continuously on-line, while the weights' values are updated.

3.2 Electrical grid

In order to demonstrate the feasibility of this proposition, anelectrical grid with a WECS system is employed. Matlab-Simulink are used for simulation, the proposed tuning performance is exhibited. The step time integration was defined variable due the simulations present slow and fast disturbances. To analyze the results, simulations are developed under different scenarios with PI controllers tuned by BSNN (dynamic parameters), ANNPI, and fixed parameters (static), FXPI. Some operating conditions are taken into account. To examine the results three situations are presented. The systems data are: for the source 120KV, 60Hz and the WECS is at 575V, 9MVA; in terminals a 500MW load is connected. Two transmission lines at 25KV connect both systems.

The first condition exhibits some control parameters training. In Fig. 4 four PI parameters are shown k_p for DC link control scheme; k_p and k_i for v_d reference value in current regulator grid side; k_p for reactive power controller in rotor side converter; finally, k_i for DC bus control is presented, Fig. 5. In these cases the parameters have and typical initial condition for this regulator purpose, after that, each one attain the better value in grid operation condition. In this case a 10 percent load at WECS terminals was increased.

Once the control parameters are first tuning the updating procedure goes on based on learning on-line rule. The second situation is a slow perturbation when the wind speed changes from 8 to 14 m/s in 6 seconds. After that, the parameters are retuned to reach better performance in this new operation condition.

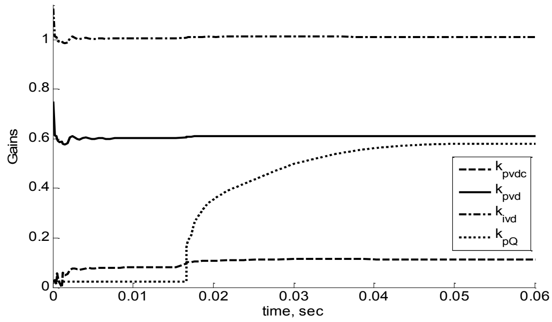

Fig. 4. Gains in controllers for v_{dc}, v_d and$Q$.

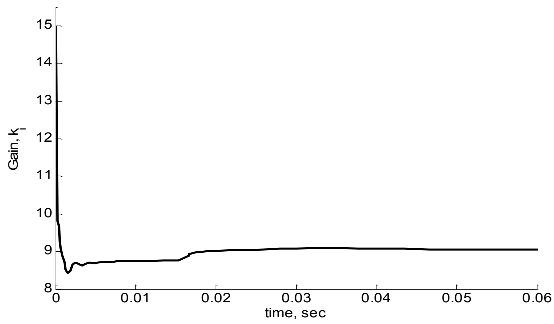

Fig. 5. First updating for k_i in controller 1.

Fig. 6 shows that the dynamic behavior of the proposed scheme is better than that of the conventional PI with fixed parameters in DC voltage when the system is subject to wind speed change, similar transient characteristics in reactive power exchange is observed, Fig. 7.

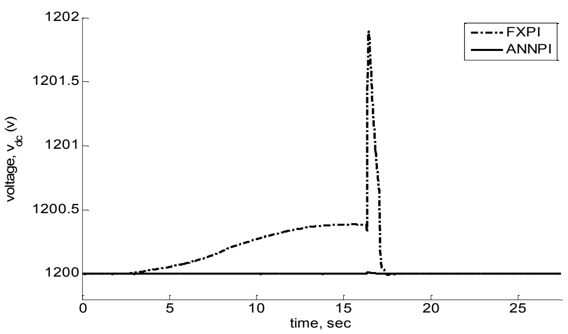

Fig. 6. DC link voltage performance, *case 2*.

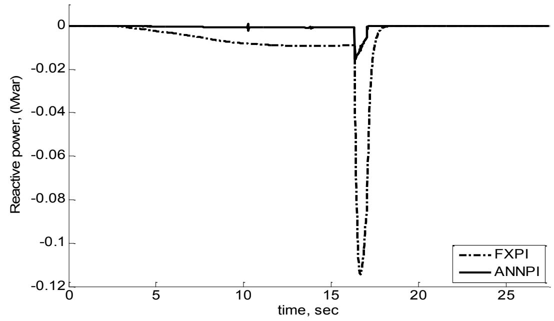

Fig. 7. Reactive power exchange, *case 2*.

The third case validates the appropriate system evolution when the load is increased in WECS terminals in 200 percent, from 500MW to 1500MW.Fig. 8 exhibits the DC voltage evolution; about 0.02 seconds to achieve the stationary state are needed, otherwise, for FXPI the overshoot and settling time are larger.

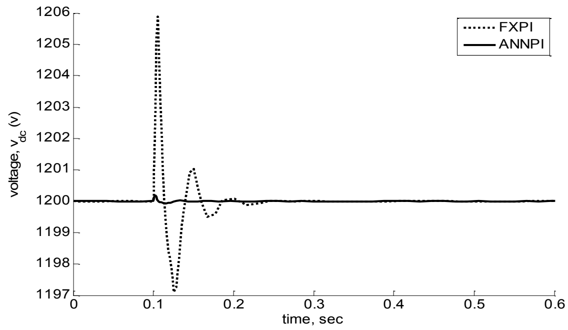

Fig. 8. DC link voltage performance, *case 3*.

Active powers in WECS terminals and the electrical grid middle are presented in Fig's. 9-10. The results are in accordance with case 2. In Fig. 10 we can appreciate that the source-side instead receive 6.2MW, only obtain 5.2MW due one load are added. As shown in Fig's.6-9 the adaptive controller parameters performance can decrease the oscillations amplitude and transient time under different operating conditions, respect to the behavior with fixed control parameters. Similar performance is exhibited with other variables in cases 2 and 3 for instancev_{dc}, Q and, i_d.In this paper we integrate only five adaptive parameters. The PI controller parameters in steady state after case 3 are:grid side (v_{dc}, v_d, v_q) [0.0897, 8.8267, 0.5978, 1.0011, 1.2542, 2.0286]; rotor side (i_{rd}, i_{rq}) [0.7045, 56.3987, 2.0417, 47.7654], k_p and k_i, respectively. The parameters are updated every sampled time by BSNN.

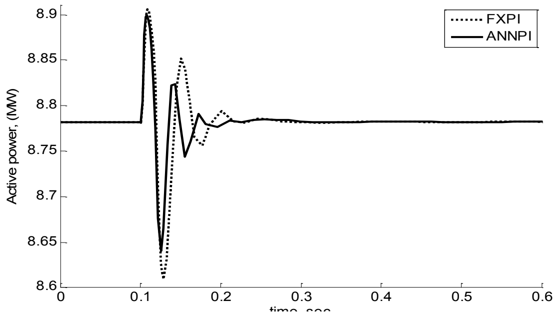

Fig. 9. Active power in WECS terminals, *case 3*.

4 Conclusion

The aim of this paper is to show the performance of adaptive PIparameters asa meanto tune linear

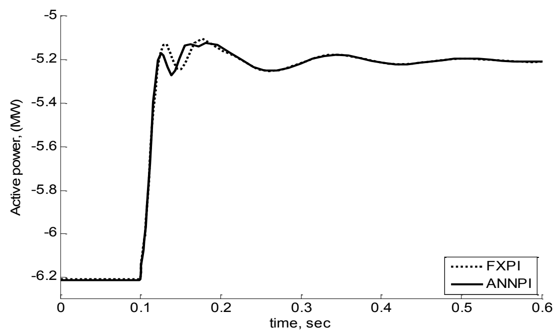

Fig. 10. Active power flowbetween source and WECSsides connected by two lines, *case 3*.

controllers in WECS system. In order to attain such purposes a B-spline neural network-based is proposed. With this neural adaptive scheme, the possibility to implement the on-line updating parameters is potential due to it has learning ability and adaptability, robustness, simple algorithm and fast calculations This is desirable for practical hardware implementation in power stations.

Unlike the conventional technique, the B-spline NN exhibits an adaptive behavior since the weights can be adapted on-line responding to inputs and error values as they arise. Also, it can take into account nonlinearities, un-modeled dynamics, and un-measurable noise. Simulations on electrical grid under different disturbances and operating conditions, demonstrate the effectiveness and robustness of the proposed strategy.

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References:

[1] Hoa M. Nguyen, D. Subbaram Naidu, “Advanced Control Strategies for Wind Energy Systems: An Overview”, 2011 IEEE PES Power Systems Conference& Exposition (PSCE).

[2] S. Niu, K.T. Chau, J.Z. Jiang, and C. Liu, “Design and control of a new double-stator cup-rotor permanent-magnet machine for wind power generation,” IEEE Trans. Magnetics, vol. 43, No. 6, pp. 2501-2503, 2007.

[3] Yi Wang, Lie Xu, “Coordinated Control of DFIG and FSIG-Based Wind Farms Under Unbalanced Grid Conditions”, IEEE Trans. Power Delivery, vol. 25, No. 1, pp. 367-377, January 2010.

[4] MostafaSoliman, O. P. Malik, David T. Westwick, “Multiple Model Predictive Control for Wind Turbines With Doubly Fed Induction Generators”, IEEE Trans. Sustainable Energy, vol. 2, No. 3, 2011.

[5] F. M. Hughes, O. Anaya-Lara, N. Jenkins, and G. Strbac, “Control of DFIG-based wind generation for power network support,” IEEE Trans. Power Systems, vol. 20, No. 4, pp. 1958–1966, 2005.

[6] JanethAlcalá, Víctor Cárdenas, Emanuel Rosas CiroNúñez, “Control system design for bi-directional power transfer in Single-Phase Back-to-Back converter based on the linear operating region”, Applied Power Electronics Conference and Exposition (APEC) IEEE, pp. 1651-1658, 2010.

[7] Van-Tung Phan, Hong-Hee Lee, “Performance Enhancement of Stand-Alone DFIG Systems With Control of Rotor and Load Side Converters Using Resonant Controllers”, IEEE Trans. Industry Applications, vol. 48, No. 1, 2012.

[8] J. Hu, H. Nian, B. Hu, Y. He, and Z. Q. Zhu, “Direct active and reactive power regulation of DFIG using sliding-mode control approach,” IEEE Trans. Energy Conversion, vol. 25, No. 4, pp. 1028–1039, 2010.

[9] H. Camblong, I. M. de Alegria, M. Rodriguez, and G. Abad, “Experimental evaluation of wind turbines maximum power point tracking controllers,” Energy Convers. Manage., vol. 47, pp. 2846–2858, 2006.

[10] M. Sedighizadeh, D. Arzaghi-Harris, and M. Kalantar, “Adaptive PID control of wind energy conversion systems using RASP1 mother wavelet basis function networks,” IEEE Conference in TENCON, vol. C, pp. 524 – 527, Nov. 2004.

[11] R. Pena, J.C.J.C Clare, G.M. Asher, “Doubly fed induction generator using back-to-back PWM converters and its application to variable-speed wind-energy generation”, IEE Proceedings Electric Power Applications 143 (3)(1996) 231-241.
[12] B. Wu, Y. Lang, N. Zargari, S. Kouro, “Power Conversion and Control of Wind Energy systems”, IEEE Press, cap. 2, 2011.
[13] Brown, and C. Harris, “Neurofuzzy Adaptive Modelling and Control,” Prentice Hall, 1994.