Power Generation and Active Filtering of Harmonic Currents Using a New Synchronous Generator for Wind Power Applications

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Abstract

In this paper, we propose a Wind Energy Conversion System (WECS) at fixed speed using a New Doubly Fed Synchronous Generator (DFSG) controlled on the rotor side through converters with two winding fields, to generate active and reactive power to the grid and cancel the harmonics generated by the non linear load (diode rectifier). To verify the validity of the proposed method, a dynamic model of the proposed system has been simulated, for different operating points.

1. Introduction

The most percentage of the installed wind turbines in the world, stall-regulated turbines with synchronous generators monitoring at constant speed. The stator windings are directly connected to the line grid, while the rotor windings are supplied by an inverter/boost converter.

This technology is simpler than the variable speed one and precedes it in time. Synchronous generator machines have proven their efficiency due to qualities such as robustness, low cost and simplicity when it is directly connected to the grid. This is due mainly to the reduced mechanical loads on the wind turbines. However, a secondary advantage is the increased possibilities of control of both active and reactive power to allow easier integration of wind turbines into the power system and the third is the filtering of the harmonics of nonlinear load.

In recent years, with the increase of nonlinear loads drawing nonsinusoidal currents, power quality distortion has become a serious problem in electrical power systems. The active filters are the most known solution. Recently, another harmonic current mitigation uses variable speed WECS with doubly fed induction generator DFIG is proposed to achieve simultaneously a green active and reactive power source with active filtering capability [1,6,7,8]. T. Abolhassani & all [9,10] and Fuyuta T & all [11], proposes an electromechanical active filter to cancel 5th and 7th harmonics generated by nonlinear loads. The proposed approach consists of a synchronous generator with modification to its field excitation. It is shown that, by injecting 2nd, 4th and 6th harmonic currents into the field, a standard synchronous generator can be modified to generate 5th and 7th harmonics in the stator winding connected to the electric utility.

In this paper, we study simultaneous power generation and harmonics current mitigation using fixed speed WECS with a new synchronous generator DFSG/Active Filter, this machine has two rotor field winding independently, one following the axis d the other following axis q. Each winding is connected to its own single phase inverter (4 switches). The stator is connected directelly to the grid. The harmonics currents absorbed by the non-linear load connected to the point common of coupling are extracted. It is well known that those currents drawn from the grid are rich in harmonics with the orders of (6k±1), that is 5, 7, 11,... extracting harmonics from the load currents by the computation of instantaneous power *p–q* and translate from abc coordinate to *dq* coordinate, the component d is the reference of field cuircuit *d*, and the other for field *q*. the analysis and simulation results show quite good performance of the proposed approach technique.

2. New doubly fed synchronous generator model

A model commonly used for the synchronous generator is the Park's model [15]. Linear magnetic circuits are assumed. Using the motor convention, the synchronous Park's model can be expressed as [1,2,3,15]

$$V_d = R_s i_d - \omega_s (L_q i_q + M_{fq} i_{fq}) + \frac{d}{dt}(L_d i_d + M_{fd} i_{fd}) \quad (1)$$

$$V_q = R_s i_q + \omega_s (L_d i_d + M_{fd} i_{fd}) + \frac{d}{dt}(L_q i_q + M_{fq} i_{fq}) \quad (2)$$

$$V_{fd} = R_f i_{fd} + \frac{d}{dt}(M_{fd} i_d + L_{fd} i_{fd}) \quad (3)$$

$$V_{fq} = R_f i_{fq} + \frac{d}{dt}(M_{fq} i_q + L_{fq} i_{fq}) \quad (4)$$

Where V is the voltage, i the current, R the resistance and ω_s the electrical speed of the rotor. The subscripts s and f indicate stator and rotor quantities. In a wind turbine, the stator is directly connected to the grid, which means that the stator voltage Vs is determined by the grid. The rotor voltage Vf is controlled by a converter and used to perform the machine control.

With Ld,q and Lf being the stator and rotor inductance, respectively. Mf is the magnetizing inductance.

In order to present the generator equations (1,2,3,4) in the standard state space form, it is necessary to solve them for the state derivatives and collect the input and state variables into matrices. The four equations containing the state derivatives may be represented as follows

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx + Du \end{aligned} \quad (5)$$

This system of first order differential equations is known as the state equation of the system and *x(t)*is the state vector and *u(t)* is the input vector. The second equation is referred the output equation. *A* is called the state matrix, *B* is in the input matrix, *C* is the output matrix and *D* the direct transition matrix.

$$B = inv[L] \tag{6}$$

$$A = -[B][R] \tag{7}$$

where

$$[R] = \begin{bmatrix} R_s & -w_s L_q & 0 & -w_s M_{fq} \\ w_s L_d & R_s & w_s M_{fd} & 0 \\ 0 & 0 & R_f & 0 \\ 0 & 0 & 0 & R_f \end{bmatrix} \tag{8}$$

$$[L] = \begin{bmatrix} L_d & 0 & M_{fd} & 0 \\ 0 & L_q & 0 & M_{fq} \\ M_{fd} & 0 & L_{fd} & 0 \\ 0 & M_{fq} & 0 & L_{fq} \end{bmatrix} \tag{9}$$

We have for the model of the used DFSG $L_d=L_q$ and $M_{fd}=M_{fq}$, thus the formula of the electromechanical torque became as follows

$$C_{em} = \frac{3}{2} P(\phi_{fd} i_q - \phi_{fq} i_d) \tag{10}$$

and the flux linkages are

Stator flux

$$\phi_d = L_d i_d + M_{fd} i_{fd} \tag{11}$$

$$\phi_q = L_q i_q + M_{fq} i_{fq} \tag{12}$$

Rotor flux

$$\phi_{fd} = L_{fd} i_{fd} + M_{fd} i_d \tag{13}$$

$$\phi_{fq} = L_{fq} i_{fq} + M_{fq} i_q \tag{14}$$

Assuming that the stator resistance is negligible compared with the magnetizing reactance and also that the stator flux vector has a constant magnitude and rotates at a constant angular speed equal to the supply frequency, and orientate the stator vector flux towards the *d* axis, one can write

$$\phi_d = \phi_s \tag{15}$$

$$\phi_q = 0 \tag{16}$$

one can also write

$$V_d = 0 \tag{17}$$

$$V_q = w_s \phi_s \tag{18}$$

We extract the reference rotor current from equation (1) and (2) to get the following equations

$$i_{fd}^* = \frac{1}{M_{fd}} \left(\frac{V_q}{w_s} - L_d i_d^* \right) \tag{19}$$

$$i_{fq}^* = \frac{1}{M_{fq}} (-L_q i_q^*) \tag{20}$$

with

$$\begin{cases} P_s = v_{sd} i_{sd} + v_{sq} i_{sq} = v_{sq} i_{sq} \\ Q_s = v_{sq} i_{sd} - v_{sd} i_{sq} = v_{sq} i_{sd} \end{cases} \tag{21}$$

The stator references currents are:

$$i_q^* = \frac{P^*}{V_q} \tag{22}$$

$$i_d^* = \frac{Q^*}{V_q} \tag{23}$$

Where P*,Q* active and reactive powering the stator winding to grid.

After all (3) and (4)

$$V_{fd} = R_f i_{fd} + \left(L_{fd} - \frac{M_{fd}^2}{L_d}\right) \frac{d}{dt} i_{fd} \tag{24}$$

$$V_{fq} = R_f i_{fq} + \left(L_{fq} - \frac{M_{fq}^2}{L_q}\right) \frac{d}{dt} i_{fq} \tag{25}$$

3. Regulator syntheses

Using (24) and (25), the transfer function of rotor is (Fig. 1)

$$RF = \frac{1}{R_f + \left(L_f - \frac{M_{fd}^2}{L_d}\right) p} \tag{26}$$

In order to eliminate the zero present on the transfer function, see Fig.1

$$\frac{K_p}{K_i} = \frac{1}{R_f} \left(L_f - \frac{M_{fd}^2}{L_d}\right) \tag{27}$$

The transfer function in loop closed is expressed then by

$$Tf = \frac{1}{1 + \frac{R_f}{K_i} p} \tag{28}$$

and the system time is

$$\tau = \frac{R_f}{K_i} \qquad (29)$$

4. Description of the proposed method

4.1. Harmonics Current Extraction

To perform the active filtering function, the load conditioner injects load harmonic currents. The power level of the load conditioner and the amplitudes of each individual harmonic current determine the lowest harmonic current that the load conditioner can handle.

Harmonic currents are obtained by subtracting the DC component from the total currents. The advantage of using this kind of high-pass filter structure is that there is no phase shift in the extracted harmonics components. A moving average operand is a good choice to implement the low pass filter due to its simplicity and accuracy.

Follow by detecting the amplitude and phase of $m = 1 \pm 6k$ harmonics, the non linear current for phase (A) is:

$$i^*_{La} = \sum_{k=1}^{\infty} \sqrt{2} i_{6k-1} \, sin[(6k-1)(w_s t - \varphi_{6k-1})] + \sqrt{2} i_{6k+1} \, sin[(6k+1)(w_s t - \varphi_{6k+1})] \qquad (30)$$

where

$$\sqrt{2} i_{6k-1} = (-1)^k \left(\frac{I_L}{6k-1}\right) \text{ and } \sqrt{2} i_{6k+1} = (-1)^k \left(\frac{I_L}{6k+1}\right)$$

The transformation α–β of a three-phase system without neutral connected is defined by the relations:

$$\begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \qquad (31)$$

The instantaneous power for the three-phase system is as follows¶

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \cdot \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \qquad (32)$$

By observing the formulations of P and Q, it is possible to put them in the following form

$$p = \overline{p} + \tilde{p} \text{ and } q = \overline{q} + \tilde{q} \qquad (33)$$

If we put

$$\Delta = v_\alpha^2 + v_\beta^2 \qquad (34)$$

We obtain

$$\begin{bmatrix} \tilde{i}_\alpha \\ \tilde{i}_\beta \end{bmatrix} = \frac{1}{\Delta} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \cdot \begin{bmatrix} \tilde{p} \\ \tilde{q} \end{bmatrix} \qquad (35)$$

Finally the current reference given by the:

$$\begin{bmatrix} i^*_{ta} \\ i^*_{tb} \\ i^*_{tc} \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} \tilde{i}_\alpha \\ \tilde{i}_\beta \end{bmatrix} \qquad (36)$$

The power converter system control block diagram is shown in Fig 2. The load conditioner is controlled with a current loop compensator superimposed by a voltage compensator to control its DC link voltage. The current reference generator is the key for the load conditioner to perform the active filtering. The most important control aspect of the load conditioner is the generation of the current references.

To obtain the references currents control of active filter, it is necessary to pass from the *abc* co-ordinates to the *dq* as follows:

$$\begin{bmatrix} i^*_{td} \\ i^*_{tq} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \sin(\theta) & \sin(\theta - 2\pi/3) & \sin(\theta + 2\pi/3) \\ \cos(\theta) & \cos(\theta - 2\pi/3) & \cos(\theta + 2\pi/3) \end{bmatrix} \begin{bmatrix} i^*_{ta} \\ i^*_{tb} \\ i^*_{tc} \end{bmatrix} \qquad (37)$$

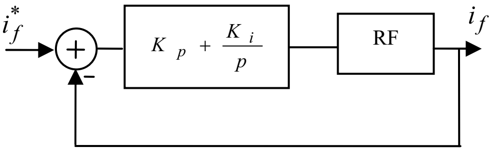

Fig.1. Schema bloc of regulation system

4.2. Front End Converter Control

The three phase AC/DC inverter shown in Fig.2 is an attractive topology for use as a front end power processing unit at higher power levels. It converts three phase input voltage to regulate DC link voltage with very low distortion in voltage and current on the AC side and DC side, minimum voltage and current stresses in the components, bidirectional power flow capability. Also, it provides unity power factor and draws continuous input currents.

The PWM rectifier has an inner current controller in rotating co-ordinates and an outer voltage loop. The DC error voltage is passed through a compensator to generate I_{ref} (current reference), as the *q* channel is responsible for the power transfer. The *d-q* co-ordinates axis are aligned with respect to the input line voltages such that V_d, as result, the d channel current reference, I_{dref} is set to zero in order to achieve unity power factor. The output of the current controller are the duty cycles d_d and d_q.

The quadrature and direct grid side current demand can be derived from the active and reactive power references P^*, Q^*

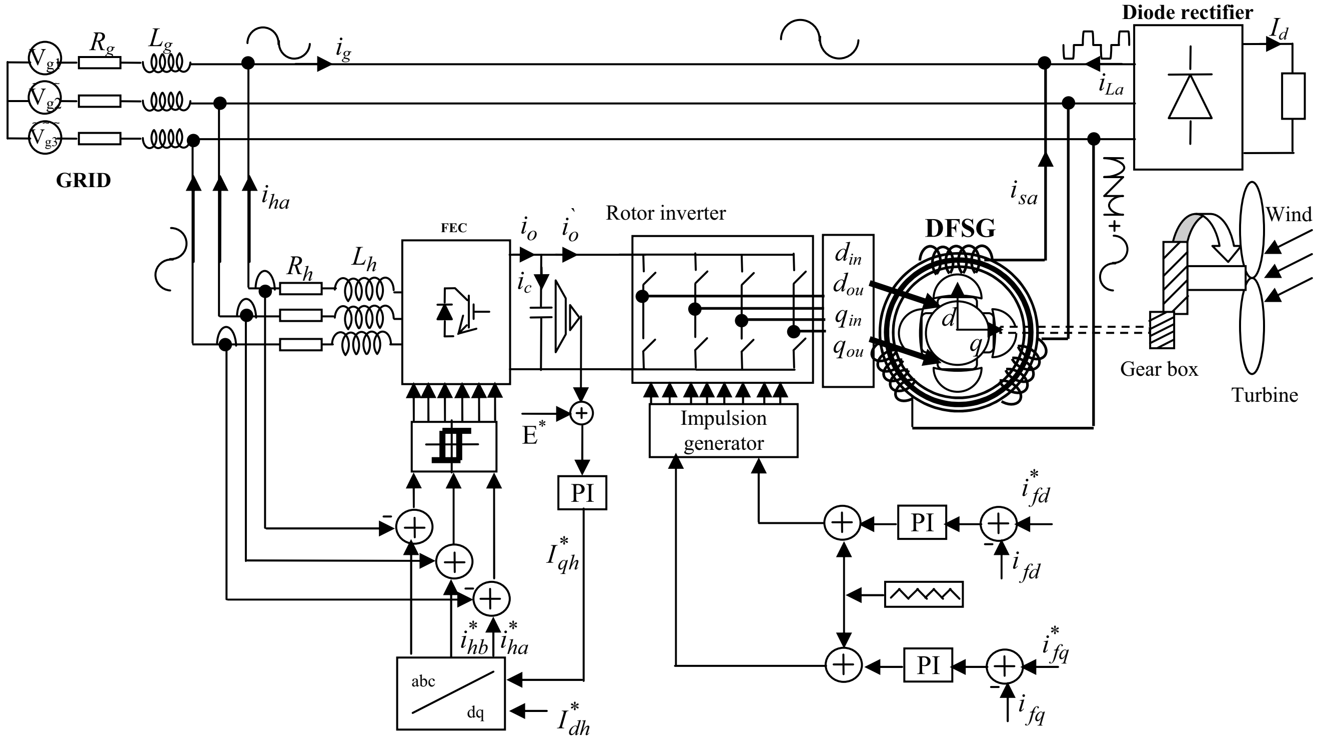

Fig.2. Block diagram of the proposed method.

$$\begin{cases} i^*_{q-reactive} = \dfrac{P^*_g}{v_{ds}} \\ i^*_{d-active} = \dfrac{Q^*_g}{v_{ds}} \end{cases} \qquad (38)$$

Harmonics currents needed for the compensation of non-linear load current. i^*_{td} and i^*_{tq} can be derived as follows:

$$i^*_{fd} = i^*_{d-reactive} + i^*_{td} \qquad (39)$$

$$i^*_{fq} = i^*_{q-active} + i^*_{tq} \qquad (40)$$

The controller voltage and current sources in the average model are represented in rotating co-ordinates as:

$$\begin{aligned} \frac{di_{dh}}{dt} &= \frac{1}{3L_g}\left(V_{gd} + 3\omega L_g i_{qh} - d_{dh}V_o\right) \\ \frac{di_{qh}}{dt} &= \frac{1}{3L_g}\left(V_{gq} - 3\omega L_g i_{dh} - d_{qh}V_o\right) \\ \frac{dV_c}{dt} &= \frac{1}{C}\left(\frac{3}{2}\left(d_{dh}i_{dh} + d_{qh}i_{qh}\right) - i_o\right) \\ V_o &= V_c + R_c\left(\frac{3}{2}\left(d_{dh}i_{dh} + d_{qh}i_{qh}\right) - i_o\right) \end{aligned} \qquad (41)$$

with $L = L_g + L_h$ and $R = R_g + R_h$

So, the current i_o is given by

$$i_o = \frac{3}{2}(d_{dh}i_{dh} + d_{qh}i_{qh}) \qquad (42)$$

where i_h is the grid inverter current

$$i_o = S_1 i_{af} + S_2 i_{bf} + S_3 i_{cf} \;\&\; i^`_o = S^`_1 i_{fd} + S^`_2 i_{fq} \qquad (43)$$

$S^`$ Rotor inverter switch
S Grid inverter switch

and

$$S' = \begin{cases} 1 \quad if \quad \Delta i_f < 0 \\ -1 \quad if \quad \Delta i_f > 0 \end{cases} \qquad (44)$$

5. Simulation Results

In order to validate the approach presented in this paper, we applied the proposed SGDF command strategy for the operation mode in active filtering. Figure 3 shows the action of the DFSG as active filter on the grid current. The Total harmonics distortion (THD), reduced of 30% at roughly 3%

Figure 4 shows the double action of SGDF as active filter and reactive power compensator.

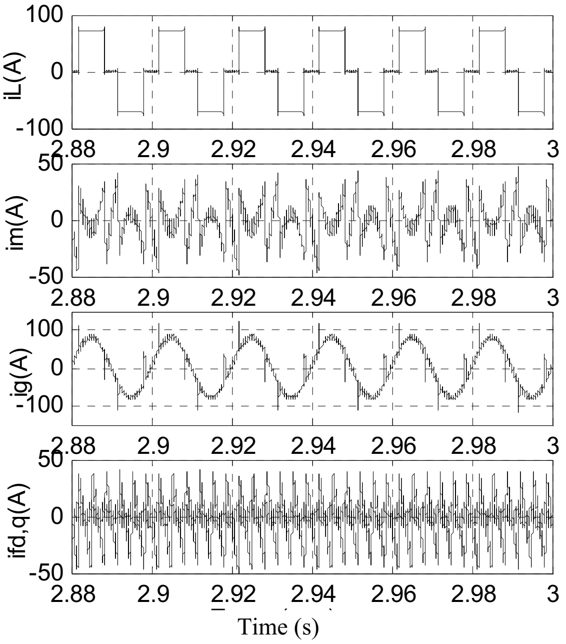

Fig.3. *il* Load current, *im* grid converter current, *ig* grid current, *ifd,q rotor currents*

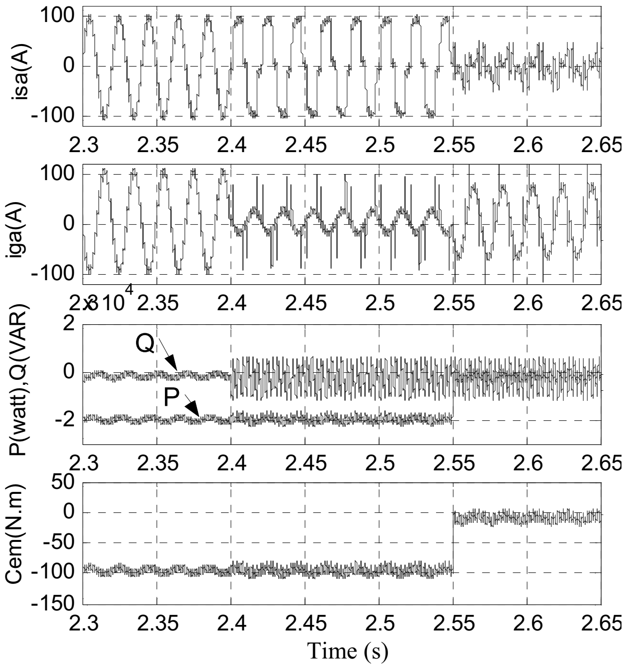

Fig. 4. *isa* stator current, *iga* grid current, *P,Q* active and reactive power, *Cem* electromagnetic torque

3. Conclusion

Due to the increase of nonlinear loads in electrical power systems, which produce current and voltage harmonics, the problem of harmonics has become serious, affecting power quality. There are many problems associated with the use of passive filters. Novel Synchronous generator/Active filters are the emerging devices, which can perform the job of harmonics cancellation properly in plus of its use as power generator.

4. References

[1] A. Gaillard a, P. Poure “Variable speed DFIG wind energy system for power generation and harmonic current mitigation” Renewable Energy 34 (2009) 1545–1553

[2] Ahmet Serdar Yilmaz, Zafer Özer « Pitch angle control in wind turbines above the rated wind speed by multi-layer perceptron and radial basis function neural networks» Expert Systems with Applications 36 (2009) 9767–9775

[3] F. Poitiers, T. Bouaouiche, M. Machmoum « Advanced control of a doubly-fed induction generator for wind energy conversion » Electric Power Systems Research 79 (2009) 1085–1096

[4] Badrul H. Chowdhury, Srinivas Chellapilla “Double-fed induction generator control for variable speed wind power generation” Electric Power Systems Research 76 (2006) 786–800

[5] M. Martinsa, A. Perdana «Validation of fixed speed wind turbine dynamic models with measured data»Renewable Energy 32 (2007) 1301–1316

[6] T. Abolhassani, Prasad Enjeti` Integrated Doubly-Fed Electric Alternator/Active Filter (IDEA), a Viable Power Quality Solution, for Wind Energy Conversion Systems

[7] P. Poure, S. Saadate ` Filtrage Dynamique D'harmoniques D'un Réseau E1ectrique a L'aide D'une Machine a Double Alimentation Commandée par Le Rotor` J. Phys. III France 5 (1995) 2087-2099

[8] T. Abolhassani, Peyman Niazi`Sensorless Integrated Doubly-Fed Electric Alternator/Active Filter (IDEA) for Variable Speed Wind Energy System` Proc. IEEE Industry Application Society 2003.

[9] T. Abolhassani, A. Toliyat « Harmonic Compensation Using Advanced Electric Machines » IECON'01: The 27th Annual Conference of the IEEE Industrial Electronics Society

[10] M. Abolhassani, H.A. Toliyat, P. Enjeti, “An Electromechanical Active Harmonic Filter,” Proceedings of the International Conference on Electric Machines and Drives (IEMDC’01).

[11] Fuyuta T, Masatoshi T « Harmonic Compensation Using a Synchronous Machine with Resonant Field Circuit» IEEE Transaction on Energy Conversion, Vol. 12, No. 2, June 1997.

[12] Nirmal.K.G « Comparison of International and NEMA Standards for salient Pole Synchronous Machines »IEEE Transaction On Energy Conversion, Vol.14, No. 1, March 1999.

[13] Eduard. M, H. Edward. M « Power Quality Issues in a Hybrid Power System» IEEE Transactions On Industry Applications, Vol. 38, No. 3, May/June 2002

[14] R. Datta and V. T. Ranganathan « Variable-Speed Wind Power Generation Using Doubly Fed Wound Rotor Induction Machine—A Comparison With Alternative Schemes» IEEE Transactions On Energy Conversion, Vol. 17, No. 3, September 2002

[15] Yong Liao, Li Ran, Ghanim A. Putrus « Evaluation of the Effects of Rotor Harmonics in a Doubly-Fed Induction Generator With Harmonic Induced Speed Ripple» IEEE Transactions On Energy Conversion, Vol. 18, No. 4, December 2003

[16] Amit Kumar Jain,V. T. Ranganathan « Wound Rotor Induction Generator With Sensorless Control and Integrated Active Filter for Feeding Nonlinear Loads in a Stand-Alone Grid» IEEE Transactions On Industrial Electronics, Vol. 55, No. 1, January 2008

[17]Frede Blaabjerg, Zhe Chen « Power Electronics as Efficient Interface in Dispersed Power Generation Systems» IEEE Transactions On Power Electronics, Vol. 19, No. 5, September 2004

[18] Zeliang Shu, Yuhua Guo « Steady-State and Dynamic Study of Active Power Filter With Efficient FPGA-Based Control Algorithm» IEEE Transactions On Industrial Electronics, Vol. 55, No. 4, April 2008.