DC LINK CURRENT ESTIMATION IN WIND-DOUBLE FEED INDUCTION GENERATOR POWER CONDITIONING SYSTEM

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Abstract: In this paper the implementation of the DC link current estimator in power conditioning system of the variable speed wind turbine is shown. The wind turbine is connected to double feed induction generator (DFIG). The variable electrical energy parameters delivered by DFIG are fitted with the electrical grid parameters through back-to-back power converter. The bidirectional AC-AC power converter covers a wide speed range from subsynchronous to supersynchronous speeds. The modern control of back-to-back power converter involves power balance concept, therefore its load power should be known in any instant. By using the power balance control, the DC link voltage variation at the load changes can be reduced. In this paper the load power is estimated from the dc link, indirectly, through a second order DC link current estimator. The load current estimator is based on the DC link voltage and on the dc link input current of the rotor side converter. This method presents certain advantages instead of using measured method, which requires a low pass filter: no time delay, the feed-forward current component has no ripple, no additional hardware, and more fast control response. Through the numerical simulation the performances of the proposed DC link output current estimator scheme are demonstrated.

Keywords: DC link current estimator, PWM, back-to-back power converter, power balance, DFIG.

1. INTRODUCTION

The energy provided by the renewable resources becomes a major ingredient of worldwide sustainable development. After the large hydropower system, geothermal power and solar collectors, wind power is becoming increasingly exploited and provides an important share of renewable energy. The actual European energy policies impose a high wind penetration rate in national energy supply networks.

Traditional rectifiers, uncontrolled full bridge or phase controlled, are widely used to provide DC voltage for inverters which produce serious problems regarding the harmonics content in power supply.

The using of PWM forced switching active power rectifiers is directly related to bidirectional power flow and unity power factor (Kataoka, T., 1979). The first approaches in PWM AC-AC power conversion were made by (Weichmann *et al.,* 1985) and (Ziogas

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et al., 1985, 1986). AC-AC power converters are classified into direct and indirect power converters.
In spite of indirect power converters, AC-AC direct power converters have the advantage of using small reactive elements. Feed-forward load current component was firstly introduced by Sul (Sul, *et al.*, 1990) to increase the speed response of the dc link voltage to load changes. Power flow direction control through the AC-AC converter is performed by keeping a dc link constant voltage (Uhrin, *et al.,* 1996). The reversal power flow through the power converter system is achieved by DC link current direction changing. The output power is calculated from the DC link output current (Uhrin, *et al.,* 1996).

In order to apply power balance control, the output power of the back to back power converter should be known. Many other authors have made different methods in order to obtain load power information.

One of these methods is to measure (Wu *et al.*, 1991), (Malesani *et al.*, 1995), (Singh et al., 1999) the power supplied from the inverter and to use a low pass filter. This method has as consequences in time delays in the current control. Another method is to estimate (Kim *et al.*, 1993), (Habetler T. G., 1993) the load power. The load power can be estimated from the inverter side or dc side. In the dc side case, the dc link current measurement becomes a serious problem at large inverter power rating due to the stray inductance of the bus bar system between capacitors and insulated gate bipolar transistors (Ziogas et al., 1085). The output power estimator used in the load feed-forward loop provides information about the load current (Gaiceanu, et al., 2003). The use of load feed-forward increases the dynamic response of the dc link voltage to load changes.

The estimation problem in fast processes is largely used in (Nichita, *et al.,* 1996; Rosu, *et al.,* 1998; Bose, 2002; Leon *et al*., 2009). At the same time, the estimation problem is associated with the sensorless control (Lin W.M., *el al*. 2009). By using the different available methods of power control, (Poitiers F., *et al*. 2009; Lin W.M., *et al*. 2010), the modern control approaches (Uhrin *et al.,* 1996; Gaiceanu, 2004) relieve the neccesities of including of feedforward load current component in regulating the active power.

The nonlinear (Boukhezzar B., Siguerdidjane H. 2010 a, b) and intelligent control could be added (Elshafei A.L., *et al*., 2010) in order to boost the overall control performances.

This paper is organized as follows: The mathematical model of DFIG, line side voltage source converter, DC-link and grid-side power converter the proposed control method are investigated in Section 2. The proposed DC link load current estimator is shown in Section 3. The simulation results to verify the estimator performances are shown in Section 4. The conclusion is given in Section 5.

2. MATHEMATICAL MODEL OF THE POWER SYSTEM

In Fig. 1 the well-known wind turbine power system based on DFIG is shown. Stator windings are directly connected both to three-phase grid and grid side converter, and rotor windings are connected to rotor side converter. Therefore, a bidirectional back-to-back converter with DC-link is used.

This paper serves the needs of global wind power penetration in the national power grid, while studying the way of improving the power control of a wind DFIG power conditioning system.

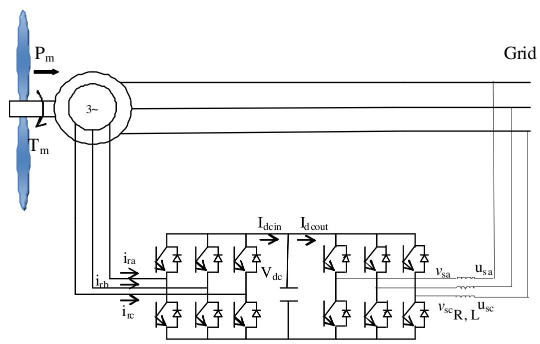

Fig.1. Wind turbine system based on DFIG and back-to-back power converter

The turbine is connected to the rotor of the generator via a shaft. Considering J the total inertia moment reduced to the DFIG rotor, ω_r as rotor angular velocity, the turbine, shaft and generator are modeled as followed:

$$(1)\quad \frac{d\omega_r}{dt} = \frac{T_e - T_s}{J}$$

where T_s is the wind turbine torque and T_e is the electromagnetic torque of DFIG:

$$(2)\quad T_e = -\frac{3}{2} p_p \left(\psi_{sd} i_{sq} - \psi_{sq} i_{sd}\right)$$

the negative sign showing that the electrical machine operates as generator, p_p being the number of pole pairs. The rest of electromagnetic torque parameters are explained in the next Section.

2.1. Rotor-Side Converter

Rotor side converter is used to control the machine speed and reactive power.

DFIG mathematical model

The well-know mathematical model for wound rotor induction machine is described by the voltage equations (stator and rotor) and of electromagnetic torque equation (Salman M., *et al.* 2004; Patin, *et al.*, 2010):

$$(3)\quad \begin{cases} v_{sd} = R_s i_{sd} + \frac{d}{dt}\psi_{sd} - \omega_s \psi_{sq} \\ v_{sq} = R_s i_{sq} + \frac{d}{dt}\psi_{sq} + \omega_s \psi_{sd} \\ v_{rd} = R_r i_{rd} + \frac{d}{dt}\psi_{rd} - (\omega_s - \omega_r)\psi_{qr} \\ v_{rq} = R_r i_{rq} + \frac{d}{dt}\psi_{rd} + (\omega_s - \omega_r)\psi_{dr} \end{cases}$$

where flux linkage equations:

$$(4)\quad \begin{cases} \psi_{sd} = L_s i_{sd} + L_m i_{rd} \\ \psi_{sq} = L_s i_{sq} + L_m i_{qs} \\ \psi_{dr} = L_r i_{rd} + L_m i_{sd} \\ \psi_{qr} = L_r i_{rq} + L_m i_{sq} \end{cases}$$

$\Psi_{sd,q}$ Stator *d-q* axis flux linkage
i_{dqs}, i_{dqr} : Stator and rotor d-q axis currents
$\Psi_{rd,q}$ Rotor d-q axis flux linkage;
L_m : Magnetizing inductance;
L_s: Stator self-inductance;
L_r: Rotor self-inductance;
R_s, R_r stator, respectively rotor per phase resistance
ω_e is the stator angular frequency,
and the relationship between inductances by:

$$(5)\quad \begin{cases} L_s = L_{ls} + L_m \\ L_r = L_{lr} + L_m \end{cases}$$

L_{ls}- stator leakage inductance; L_{lr}-rotor leakage inductance.
V_s, V_r stator, respectively rotor voltage of DFIG;

2.2. Stator-side (Front-End) converter (FEC) control:

The main objective of stator-side converter is to maintain the DC-link voltage constant regardless of the magnitude and direction of the slip power. A current-regulated PWM scheme is used: the *q* axis current is used to regulate the DC link voltage, and *d* axis current is used to regulate the reactive power. Based on Fig.2 and taking into account the inductance and resistance of the three phase filter, voltage equations across the inductor can be written as follows:

$$(6)\quad \begin{bmatrix} u_{sa} \\ u_{sb} \\ u_{sc} \end{bmatrix} = R \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} + L\frac{d}{dt}\begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} + \begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix}$$

where:

u_{Sabc} three phase system voltages
v_{Sabc} three phase line side converter terminal voltages
i_{Sabc} Three phase line side converter input currents
L Line side filter inductance
R Line side filter resistance

2.3. DC link mathematical model

By using the measured rotor currents, i_{rabc}, and the switching functions s_a, s_b and s_c, the input DC-link current, I_{dcin}, can be obtained:

$$(7)\quad I_{dcin} = s_a i_{ra} + s_b i_{rb} + s_c i_{rc}$$

where s_a, s_b and s_c can be either 0 or 1, with s = 1 indicating that the output is connected to the positive terminal of the dc-link capacitor.

The power equation of DC link (P_{dc}) can be written, as:

$$(8)\quad CV_{dc}\frac{dV_{dc}}{dt} + V_{dc}I_{dcout} = V_{dc}I_{dcin} = P_{dc}$$

where: C is the DC link capacitor, and V_{dc} is the DC link rated voltage

3. DC-LINK LOAD CURRENT ESTIMATOR

The block diagram of the second-order DC link output current estimator is shown in Fig. 2.

The input data for the current estimator are the DC link voltage $V_{dc}(p)$ and the input current of the DC link, I_{dcin}. The estimator output is the DC link load current, I_{dcout}.

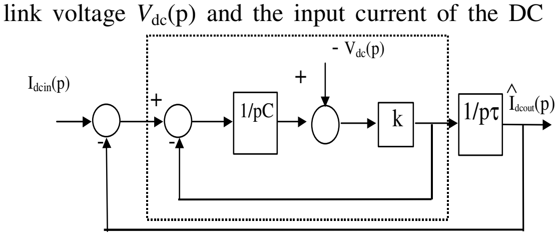

Fig. 2 DC link load current estimator

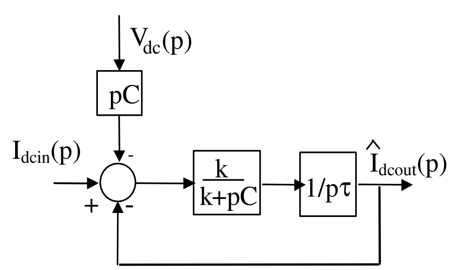

Fig.3 The redrawing estimator block

Load current estimator (Fig. 3) can be reconfigured based on the use of the automatic systems theory (algebra block diagrams) as presented in Fig.4 or in final form (Fig. 5). By applying Kirchhoff's theorem in DC link circuit and using the Laplace transform the following equation is obtained:

$$(9)\quad pCV_{dc}(p) = I_{dcin}(p) - I_{dcout}(p)$$

or in another form:

$$(10)\quad I_{dcin}(p) - pCV_{dc}(p) = I_{dcout}(p)$$

where p is Laplacian operator.

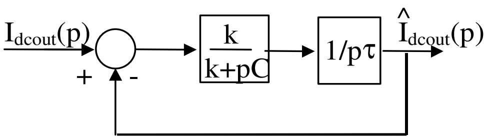

Fig. 4 The deducted DC link load current

By applying equation (10), the estimator from Fig. 3 can be redrawn like in Fig. 4 (Gaiceanu *et al.*, 2003). The DC link current I_{dcin} is obtained from the equation (7). The output dc link power is estimated as:

$$(11)\quad \hat{P}_{out} = V_{DC}\hat{I}_{OUTDC}$$

3.1. The closed loop transfer function of the DC-link current estimator

The problem consists in determining the estimator parameters in order to minimize the error between estimated and actual current load. From Fig.4, the closed loop transfer function of the estimator can be obtained:

$$(12)\quad G_0(p) = \frac{\dfrac{k}{(k+p\cdot C)\cdot p\tau}}{1+\dfrac{k}{(k+p\cdot C)\cdot s\tau}} = \frac{k}{p^2\cdot C\tau + p\cdot k\tau + k}$$

$$\Rightarrow G_0(p) = \frac{1}{p^2\cdot\dfrac{C\cdot\tau}{k} + p\tau + 1}$$

where, the denominator is putted under the form:

$$(13)\quad T_0^2 p^2 + 2\xi T_0 p + 1,$$

therefore the estimator period is:

$$(14)\quad T_0 = \sqrt{\frac{C\cdot\tau}{k}},$$

and the damping factor, repectively:

$$(15)\quad \xi = \frac{1}{2}\cdot\sqrt{\frac{k\cdot\tau}{C}}$$

The closed loop transfer function of the estimator (Fig. 5) is:

$$(16)\quad G(p) = \frac{\hat{I}_{dcout}(p)}{I_{dcout}(p)} = \frac{1}{p^2\dfrac{\tau C}{k} + p\tau + 1}$$

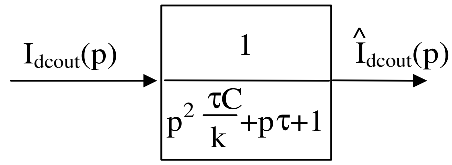

Fig.5 Final form of the DC link load current estimator

For a current step type variation $I_{dcout}(p)$, the Laplace transform becomes :

$$(17)\quad I_{dcout}(p) = \frac{I_{dcout}}{p}$$

By introducing eq. (17) in (16), the estimated DC-link load current can be deducted:

$$(18)\quad \hat{I}_{dcout}(p) = I_{dcout}\frac{1}{p(p^2\dfrac{\tau C}{k} + p\tau + 1)}$$

3.2. Determining the parameters of the DC-link current estimator

In order to find the k and τ estimator's parameters, the T_0 and ξ constants are imposed.

By imposing the damping coefficient:

$$(19)\quad \xi = \xi i$$

and taking into account the eq. (22), the τ estimator parameter can be determined as:

$$(20)\quad \tau = 4\xi_i^2\cdot\frac{C}{k}$$

To determine the required k parameter, the period of estimator T_0 is imposed:

$$(21)\quad T_0 = T_{0i} \Rightarrow k = \frac{\tau\cdot C}{T_{0i}^2} = \frac{4\xi_i^2\cdot\dfrac{C}{k}C}{T_{0i}^2}$$

Thus:

$$(22)\quad k = 2\xi_i\cdot\frac{C}{T_{0i}}$$

By introducing eq. (26) in eq (24), the τ estimator parameter results as:

$$(23)\quad \tau = 2\cdot\xi i\cdot T_{0i}$$

4. SIMULATION RESULTS

The 2nd degree order estimator was implemented for DFIG wind turbine power system 2MW. In the Appendix 1, the main data of the power system are shown. By adequate choosing of T_{0i}= 1.5000e-004, ξ_i=0.8 and using equations (22)–(23), the estimator's parameters are as follows: τ=2.4000e-

004, k=42.6667. Therefore, an acceptable step response of a load DC current can be obtained (Fig.8).

In order to demonstrate the performances of the DC-link output current estimator, DC-link voltage test generator has been created (DC-link voltage reference,V_{dcref}-Fig.6). In Fig.6 the DC-link voltage control is presented (comparison between the DC-link voltage reference and the actual DC-link voltage).

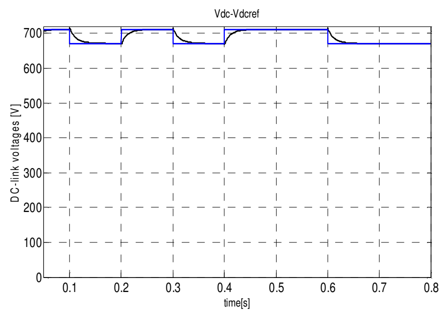

Fig.6. Comparison between the DC-link voltage reference and the actual DC-link voltage

While the DC link input current (I_{dcin}-Fig1) signal is very noisy (Fig.7a), the output signal of the estimator is very clean (Fig.8 or a zoom in versions–Figs.9,10).

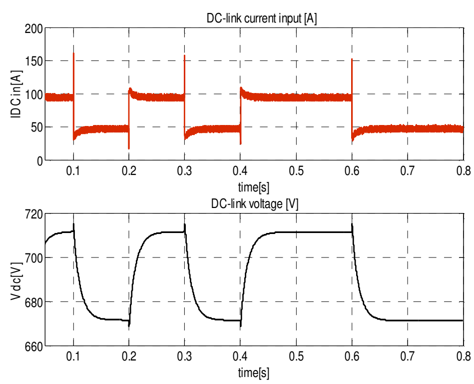

Fig.7 The inputs in the DC-link output current estimator: (a) the input current of DC link and (b) the DC link voltage

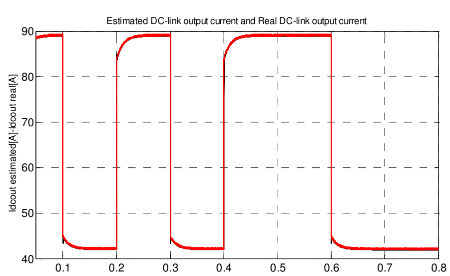

Fig.8 Simulation results. The estimator output signal ($\hat{I}_{dcout}$) and the measured one (DC load current I_{dcout}).

In order to put in evidence the performances of the proposed estimator, in Fig. 9 and Fig.10 the rise and the fall of the estimator output signal are shown.

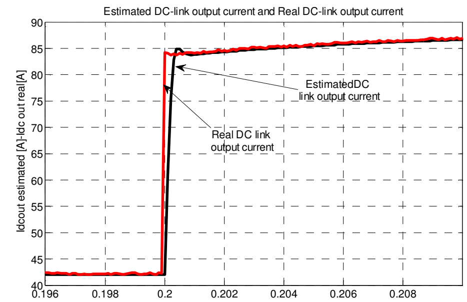

Fig.9 Zoom in comparison at rise of both DC-link output currents: measured and estimated

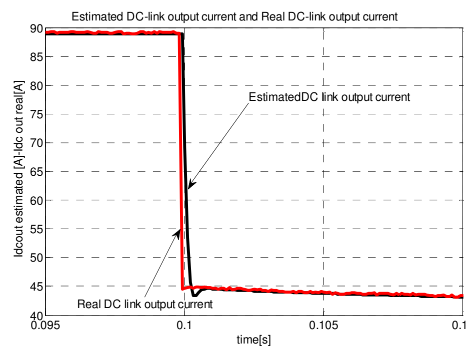

Fig.10 Zoom in comparison at fall signals of both DC-link output currents: measured and estimated

Simulations were carried out using Matlab simulation tool. The performance of a DC-link current estimator of the DFIG wind power sytem is investigated by applying a constant mechanical torque.

5. CONCLUSIONS

Since the ac-ac converter control by means of pulse-width modulation (PWM) is based on the power balance concept, its load power should be known. The load power can be estimated from the dc side through the dc load current. Thus, is mandatory to have the value information regarding the dc load current. The second-degree dc load current estimator for DFIG wind power conditioning system is developed in this paper. The main advantage of using this type of estimator is the very good approximation of DC link load current of in the presence of noise (Nichita, et al., 1996; Rosu, et al., 1998; Gaiceanu, 2004), thus solving the problems which may occur when using a current transducer. Besides the fact that the price of the entire system goes down by adjusting such an estimator, we can say that the reliability of the system also increases since it is known the fact that a transducer is considered as a factor in an automatic failure.

Another important advantage is the minimization of the dc link ripple current due to the action of the feed-forward reference current of the DC-AC connected to the grid (the components used to estimate the load power). Therefore, the utility of the dc load current estimator is important for the power control (Li, 2010).

The DC voltage regulation with good dynamic response is achieved (Fig.6) even if dc capacitance is substantially reduced. This implies also the good accuracy of the dc link load current estimation.

By using the estimated method, the diminished ripple in the actual current of the source side is obtained (Fig.8). Hence, small power losses in power components, lower current rating of power components and easier protection of the system.

Another advantages of the estimated method are: the estimated current component has no ripple, no additional hardware, and more fast control response. The 1st order dc load current estimator, presented in the (Gaiceanu, *et al.,* 2003) reference, is simpler, but the filtering of the noise is not so good.

Through the simulation results the performances of the proposed dc load current estimator are demonstrated.

6. REFERENCES

Bose B. K. (2002). *Modern Power Electronics and AC Drives* , Chapter 8, Pretice Hall PTR.

Boukhezzar B., Siguerdidjane H. (2010). Comparison between linear and nonlinear control strategies for variable speed wind turbines, *Control Engineering Practice 18,* 1357–1368.

Boukhezzar B., Siguerdidjane H. (2010). Nonlinear control with wind estimation of a DFIG variable speed wind turbinefor power capture optimization, Energy Conversion and Management 50 (2009), 885–892.

Chen Hao, Song Sun, Dionysios C. Aliprantis and Joseph Zambreno (2010). Dynamic Simulation of DFIG Wind Turbines on FPGA Boards, *Proceedings of the Power and Energy Conference at Illinois (PECI)*, pp. 39-44, February 2010

Elshafei A.L., Azzouz M.A. (2010). Adaptive fuzzy regulation of the DC-bus capacitor voltage in a wind energy 3 conversion system (WECS), *Expert Systems with Applications (2010).*

Gaiceanu M. (2004). "AC-AC converter system", *PEMD'04*, IEE, Second IEE International Conference on Power Electronics, Machines and Drives (PEMD2004), University of Edinburgh, UK: 31 March – 2 April 2004, pp 724-729, vol.2, ISBN 0 86341 383 8

Gaiceanu M., and Emil Rosu (2003). A simple dc load power estimator for quasi-direct ac-ac converter system., The Annals of "Dunarea de Jos" University of Galati, Fascicle III, ISSN 1221-454X, 2003, pp.49-54.

Habetler T. G. (1993). "A space vector-based rectifier regulator for AC/DC/AC converters," IEEE Trans. Power Electron., vol. 8, pp. 30–36, Feb.

Kataoka, T., K., Mizumachi, and S., Miyairi (1979). "A pulse-width controlled ac to dc converter to improve power factor and waveform of the ac line current," *IEEE Trans. Ind. Appl.*, **vol. IA - 15**, pp. 670-675, Nov/Dec

Kim J. S. and S. K. Sul (1993). "New control scheme for ac–dc–ac converter without dc link electrolytic capacitor," in Proc. IEEE PESC'93, pp. 300–306.

Leon A.E., Solsona J.A. (2009). J.A. On state estimation in electric drives, *Energy Conversion and Management 51 (2010),* 600–605.

Li H., Zhao B., Yang C., Chen H.W., Chen Z. (2010). Analysis and estimation of transient stability for a grid-connected wind turbine with induction generator, Renewable Energy (2010) 1-8.

Malesani L. M., L. Rossetto, P. Tenti, and P. Tomasin, (1995): "AC/DC/AC PWM converter with reduced energy storage in the DC link," IEEE Trans. Ind. Applicat., vol. 31, pp. 287–292, Mar./Apr.

Nichita, C., s.a.(1996). "Load Torque Estimator for Wind Turbine Simulators", SIMSIS '96, Galati

Patin N., Monmasson E., Louis J.-P. (2010). Modeling and control of a cascaded doubly-fed induction generator based on dynamical equivalent circuits, *Mathematics and Computers in Simulation 81 (2010),* 225–238.

Rosu, E., Gaiceanu, M., Bivol (1998). "Load Torque Estimation for AC Motors", CNAE '98, The 9th Symposium on Electrical Drives, Craiova, Romania, pp. 221-224;

Salman S. K and Babak Badrzadeh., (2004). New Approach for modelling Doubly-Fed Induction Generator (DFIG) for grid-connection studies, EWEC (European Wind Energy Conference), pp.1-13, http://www.2004ewec.info/files/23_1400_sksalman_01.pdf

Singh B. N., B. Singh, and B. P. Singh (1999). "Fuzzy control of integrated current-controlled converter–inverter-fed cage induction motor drive," IEEE Trans. Ind. Applicat., vol. 35, pp. 405–412, Mar./Apr.

Sul S.K., and T.A.Lipo (1990). "Design and performance of a high-frequency link induction motor drive operating at unity power factor," *IEEE Trans. Ind. Applicat.*, vol.26, no.3, pp. 434-440, May/June.

Uhrin R., F. Profumo(1996). "Stand alone AC/DC converter for multiple inverter applications," *Power Electronics Specialists Conference*, PESC '96 Record, 27th Annual IEEE, **Vol. 1**, pp. 120 – 126, 23-27 June

Weichmann, E. P., P.D. Ziogas, and V.R. Stefanovic (1985). "A novel bilateral power conversions scheme for variable frequency static power supplies," *IEEE Trans on Ind. Appl.*, **vol IA -21**, pp. 1225-1233, Sept./Oct

Wu R., S. B. Dewan, and G. R. Slemon (1991). "Analysis of a PWM ac to dc voltage source converter under the predicted current control with a fixed switching frequency," IEEE Trans. Ind. Applicat., vol. 27, pp. 756–764, July/Aug.

Ziogas P.D., Y.G.Kang, and V. Stefanovic (1985). "PWM control techniques for rectifier filter minimization," IEEE Trans.on Industry Appl., vol. IA-21, pp. 1206-1213, Sep../Oct.

Ziogas P.D., Y.G.Kang, and V. Stefanovic (1986). "Rectifier-inverter frequency changers with suppressed dc link components," *IEEE Trans. on Industry Appl.*, **vol. IA-22**, no.6, pp. 1027-1036, Nov.-Dec.

Appendix 1

P_n=2 [MW] – rated active power of wind turbine
f_n = 50 [Hz] – rated frequency
R_s = 1.4 10^{-3} [Ω] - stator per phase resistance
R_r = 9.92 10^{-4} [Ω] rotor per phase resistance
L_{ls} = 1.61 [mH]- stator leakage inductance
L_{lr} = 1.6 [mH]- rotor leakage inductance
L_m = 1.52 [mH]- magnetizing inductance
J=0.685 [s] – moment of inertia
p_p= 4 – pole pairs
C=4000e-6 [F] – DC link capacitor
V_{dcn} =690 [V] – DC link rated voltage
R=0.1[Ω], Line side filter resistance
L=1.75[mH], Line side filter inductance