CONTROL AND PERFORMANCE OF A DOUBLY-FED INDUCTION MACHINE FOR WIND TURBINE SYSTEMS

Lucian Mihet-Popa
"POLITEHNICA" University of Timisoara
Blvd. V. Parvan nr.2, RO-300223Timisoara
mihetz@yahoo.com

Abstract. *In this paper, the performance of a variable speed wind turbine concept with induction generator connected to the grid is investigated. Variable-speed wind turbine generator system has been modelled and simulated to study its steady state and dynamic behaviour. A doubly fed induction generator of 11 kW fed by a vector controlled back-to-back PWM-VSI inverter on the rotor side has been tested and the results compared with digital simulations. It is shown by both modelling and laboratory tests that a doubly fed induction machine can be used as a variable speed wind generator over a large speed range (±40 %).*
Keywords: *variable speed, bi-directional PWM converter, wind turbine generators (WTG).*

Introduction

Wind turbines may be designed with either synchronous or asynchronous generators, and with various forms of direct and indirect grid connection of the generator.

Generally the wind energy is generated using two operating modes of WTG [1-3, 8, 9]:

- Constant Speed – Constant Frequency (CSCF)
- Variable Speed – Constant Frequency (VSCF) control needs speed controller to obtain maximum power from the wind and a converter to change variable frequency of the generator to constant frequency of output voltage.

With variable speed the wind turbine is able to operate at its maximum power for a given wind speed. Some of advantages of VSCF-WTG against CSCF-WTG are [3, 8, 9]:

- It generates more energy by operating on a larger wind speed range;
- It reduces stresses in the drive train due to flywheel effect of the rotor;
- It minimizes the audible noise when operating in light winds;
- It simplifies the mechanical design and reduces mechanical stress.

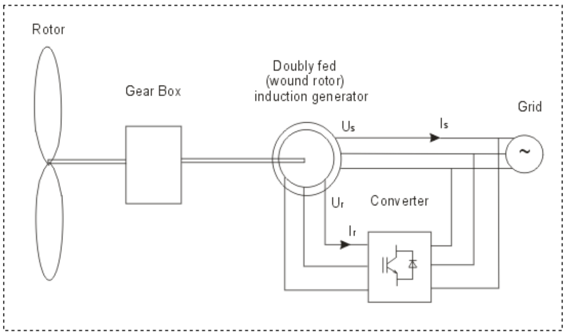
Due to the rapid development of power electronics, offering both higher power handling capability and lower price/kW, the application of power electronics in wind turbines will increase further [2].

The doubly fed induction generator can supply power at constant voltage and constant frequency while the rotor speed varies. This makes it suitable for variable speed wind energy applications. Additionally, when a bi-directional AC-DC-AC converter is used in the rotor circuit, the speed range can be extended above synchronous speed and power can be generated both from the stator and from the rotor.

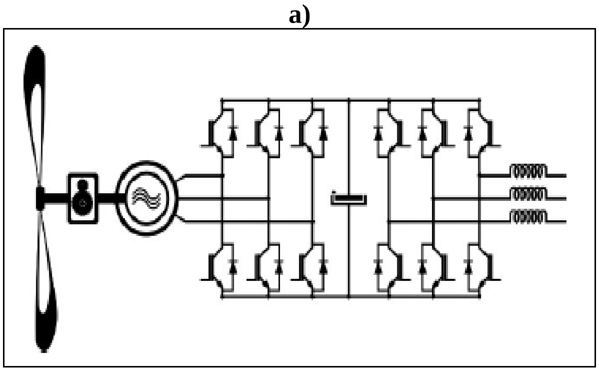
Various types of power control strategies have been suggested for application in variable speed wind turbines [1-7]. One possible implementation scheme of adjustable speed generators consists of a synchronous generator and a power converter. The power converter, which has to be rated at 1 p.u. total power system, is expensive. Compared to direct-in-line systems, the doubly fed induction generator (DFIG) systems offer the following advantages [1, 3]:

- reduced inverter cost, because inverter rating is typically 25 % of total system power, while the speed range is ±(40-60) % around the synchronous speed;
- improved system efficiency;
- power factor control can be implemented at lower cost, because the DFIG system basically operates similar as a synchronous generator.

The most commonly concepts using the asynchronous generators with speed variation applied in wind turbine configurations are displayed in Fig. 1 [1, 2, 8, 9].



a)



b)
Figure 1. Standard variable-speed wind turbine configurations using doubly fed induction machine, a) and using cage rotor induction machine, b).

Control strategy of the Doubly-Fed Induction Generator

DFIG is implemented as a variable speed, constant frequency scheme, by applying a converter to the rotor terminals of DFIG. The wind rotor determines the rotor speed, and controlling the rotor currents may control the stator power of the DFIG.

The control scheme consists of two control loops: an inner loop for controlling the rotor current, and an outer loop for controlling the stator active and reactive power, as can be seen in figure 2.

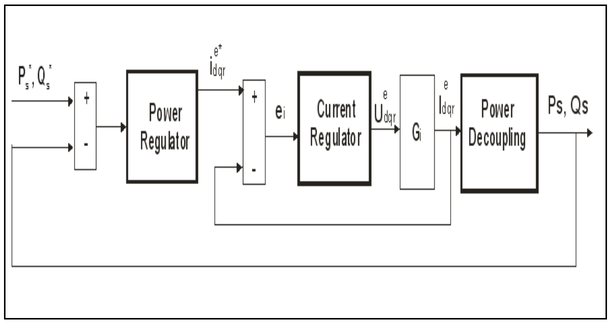


Figure 2. Simplified control scheme with an inner rotor current control loop, and an outer power control loop. Full decoupling between rotor currents is assumed.

The current regulator is designed and the closed loop transfer function (Gi) for the current loop is found. The power regulator is also designed and the closed loop performance of the power loop is evaluated.

The stator flux is chosen as a reference, the q-rotor current (I_{qr}) controls the stator reactive power (Q_s), and the rotor d-current (I_{dr}) controls the stator active power (P_s). Controlling the rotor q- and d-currents respectively may control the stator active and reactive power.

The ability to supply / subtract power to / from the rotor makes it possible to operate the DFIG at sub- and super-synchronous speed, having constant voltage and frequency on the stator terminals. Furthermore it is possible to recover slip power in the rotor and supply it back into the power grid, through which the efficiency of the machine may be increased.

The control scheme (figure 2) and the regulators are implemented in a complete simulation model also including the DFIG model, the rotor converter model and the control program developed in Ansi C and converted in Matlab-Simulink. The C-file may be executed in Simulink by means of the Matlab MEX-function., more details can be found in [8].

The model of the digital signal processor (DSP) implemented in Matlab-Simulink is shown in figure 3:

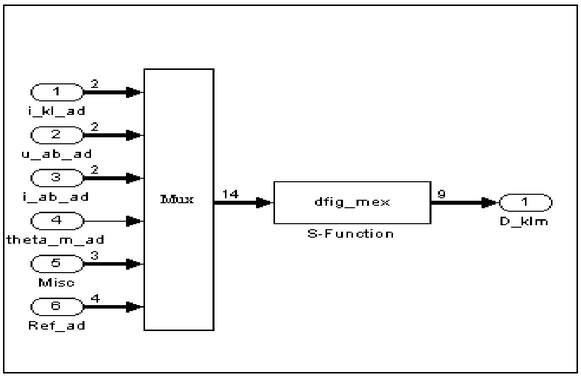


Figure 3. Model of the TMS320C32 – DSP developed in Simulink. The control algorithms written in the Ansi-C language executed using the Matlab mex S-function.

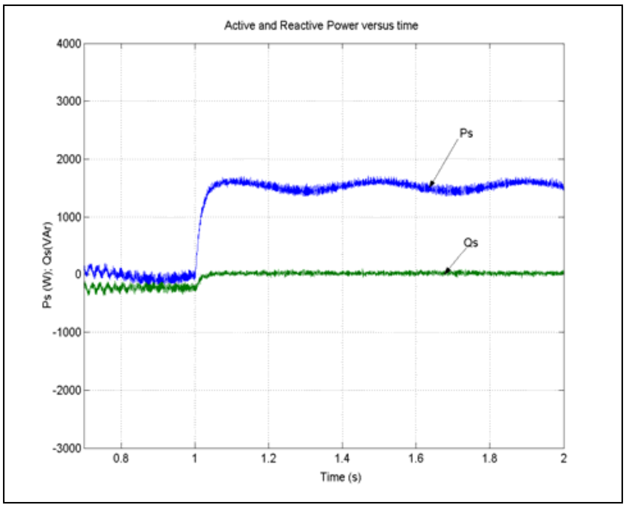
The advantage of implementing the Ansi-C file in MATLAB-Simulink is the direct connection to the implementation in DSP, and decrease in simulation time.

Simulation results

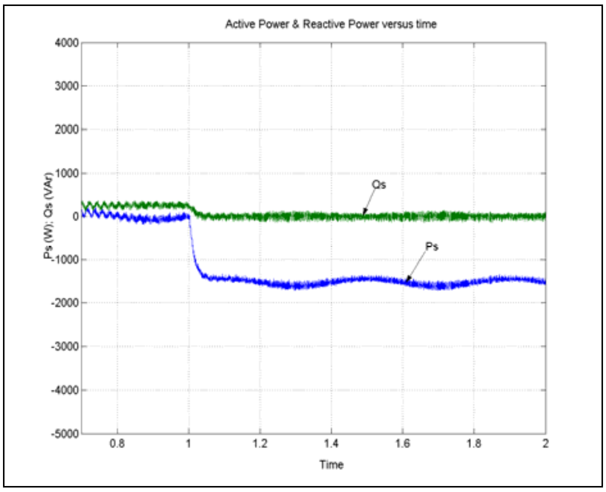
In order to evaluate the performance of implemented control strategy presented before and to analyze system response in steady state and transients the DFIG was subject to step changes in active and reactive load power with the machine driven at both sub- and super-synchronous speeds.

The transient response due to a step change in reference active power control is shown in figure 4. The figure 4 a) shows the response to a step change in the active load power from 0 to 1.5 kW, while the reference of reactive power is maintained at 0 and the corresponding stator active and reactive power (Ps, Os) of the machine are monitored. Similar transient response for generating condition is given in figure 4 b). When a step in active power is applied (t=1sec), the reactive power (Qs) shows small additional oscillations.

The simulation results indicate that the generator follows the reference very fast and is dynamically stable. It may be noted from these waveforms, that the transient responses in (Ps) and (Qs) are perfectly decoupled. The DFIG was driven by the drive system at 1125 rpm (75% of synchronous speed-sub synchronous speed operation mode).



a)



b)

Figure 4. Simulated stator active and reactive power at 1125 rpm with a step change in active power command from 0 to 1500 W (a) and with a step change in active power reference from 0 to -1500 W at t=1s, (b).

All simulations are performed with constant DFIG parameters.

The mechanical system is modelled using a first order approximation, where the time constant is determined from a step in rotor speed.

Description of the experimental set - up

The electrical machine is a doubly fed induction generator - DFIG, with slip rings, rated at 11 kW provided with a gearbox. The wind turbine rotor is emulated by use of a drive system scaled for driving the DFIG; the drive system is composed of a 15 kW induction motor and a 22-kVA-

frequency converter. Two back-to-back PWM-VSI converters with a standard control system, with a DC-link including a DC capacitor filter are used to control the rotor currents, active and reactive power flow.
The grid converter is designed to give unity power factor and is controlled by the Control Processor (CP) – board via a PC. It works as an active rectifier supplying the rotor converter with a constant DC voltage. The measurement and control system is composed of a PC with a digital signal processor (TMS320C32 DSP), interfaces and transducers for measuring stator and rotor currents, stator voltages, and rotor speed, as can be seen in figure 5.

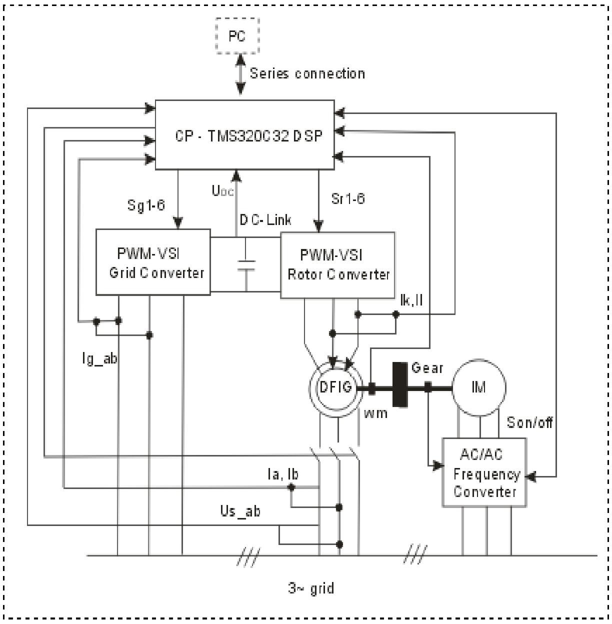
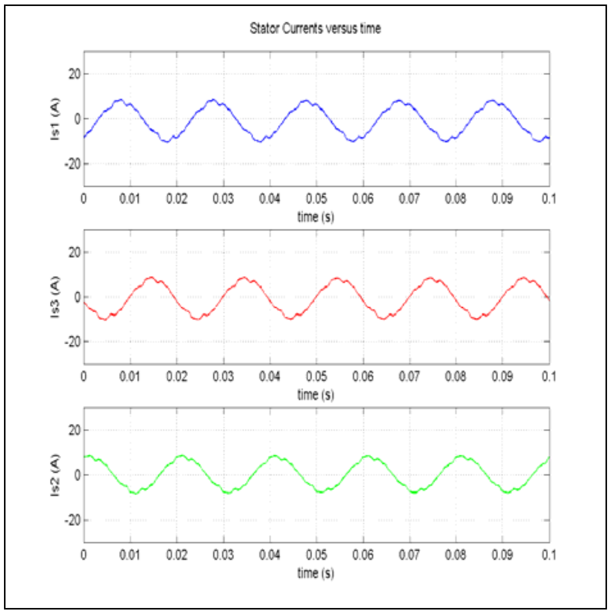


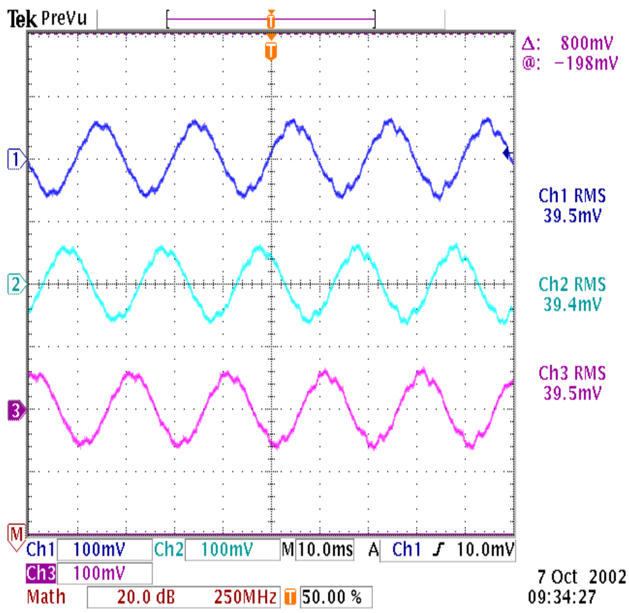
Figure 5. Schematic diagram of the experimental rig.

Comparison between simulation and experimental results

Tests and simulations were performed to examine the system performance in steady state and to validate the Matlab-Simulink implemented system developed for a variable speed wind turbine with DFIG.



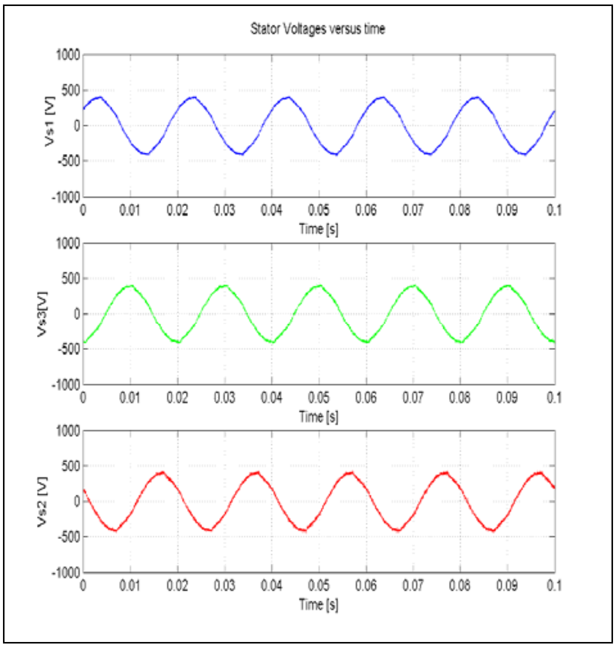
a)



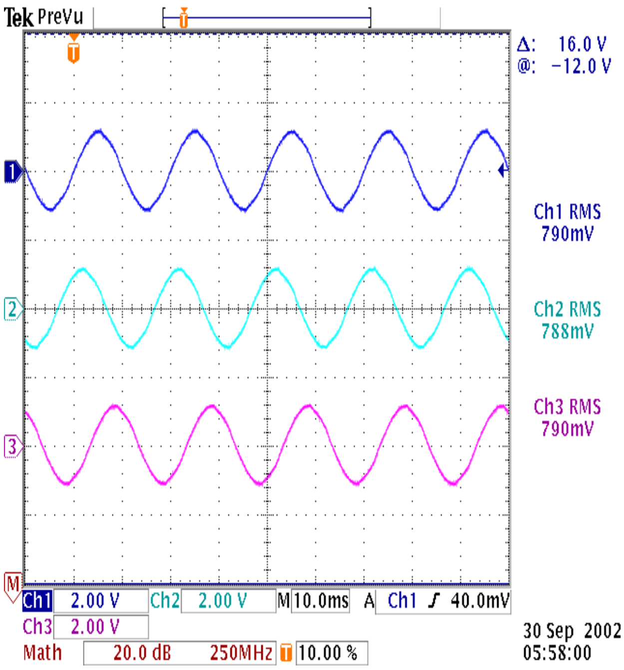
b)

Figure 6. The simulated stator currents of DFIG (a) using Matlab-Simulink and measured stator currents (b) by an Oscilloscope in steady state at P=4 kW and n=1475 rpm (sub-synchronous operation mode). Scaling factor of measured stator currents is 4 (mV/A).

Figures 6 and 7 show the steady-state waveforms of stator currents and stator voltages of the DFIG running at 1475 rpm (sub-synchronous speed operation mode) and stator power of 4 kW.



a)



b)

Figure 7. The Simulation of stator voltages in steady state (a) and measured line – line stator voltages of DFIG acquired by an Oscilloscope TDS 540. Scaling factor of measured stator voltages is 2 (mV/V).

The figure 6 shows a comparison between simulated and measured stator currents of DFIG, while in figure 7 is presented a comparison between simulated (b) and measured (a) stator voltages of DFIG. The measured data were acquired by an Oscilloscope, while the simulation results were performed by Matlab / Simulink. The correspondence between simulations and experiments is very good as can also be seen in figure 6 and figure 7.

Conclusions

In this paper a variable speed wind turbine concept using doubly fed induction generator connected to the grid was presented.
A control scheme is developed for decoupled control of active and reactive stator power of the DFIG.
The control strategy is a cascade control and contains two control loops. An inner rotor current control loop and an outer stator power control loop.
The simulation shows good dynamic performance regarding power control when the rotor speed is varied. Measurements obtained confirm the theoretical results and validate the simulation program of the variable-speed constant frequency system with the DFIG for wind power generation applications.
The doubly fed induction generator system presented offers many advantages to reduce cost and has the potential to be built economically at power levels above 1.5 MW, e.g. for off-shore applications. Additionally, when a bi-directional AC-DC-AC converter is used in the rotor circuit, the speed range can be extended above synchronous speed when active power can be generated both from the stator and the rotor. The two back-to-back PWM converters in the rotor circuit result in low distortion currents, reactive power control and both sub- and super-synchronous operations.

References

[1] Siegfried Heier, "Wind energy conversion systems", book, John Wiley & Sons Inc., New York, 1998.
[2] L.H. Hansen, L. Helle, F. Blaabjerg, E. Ritchie, S. Munk-Nielsen, H. Bidner, P. Sorensen and B. Bak-Jensen, "Conceptual Survey of Generators and Power Electronics for Wind Turbines", Riso-R-1205 (EN), December 2001.
[3] S. Muller, M. Deicke and Rik W. De Doncker, "Doubly Fed Induction Generator

Systems for Wind Turbines", IEEE Industry Applications Magazine, May-June 2002, pp. 26-33.

[4] R. Pena, 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", 1996, IEE Proceedings on Electrical Power Applications, Vol. 143, No. 3, pp. 231-241.

[5] Hirofumi Akagi and Hikaru Sato, "Control and Performance of a Doubly-Fed Induction Machine Intended for a Flywheel Energy Storage System", IEEE Transaction on Power Electronics, Vol. 17, No. 1, January 2002, pp. 109-116.

[6] Rajib Datta and V.T. Ranganathan, "Direct Power Control of Grid-Connected Wound Rotor Induction Machine without Rotor Position Sensors", IEEE Transactions on Power Electronics, vol. 16, no. 3, May 2001, pp. 390-399.

[7] D.S. Zinger, E. Muljadi, "Annualized wind energy improvement using variable speeds", Industrial & Commercial Power Systems technical Conference, 1997. Conference Records, Papers presented at the 1997 Annual Meeting, IEEE 1997, 11-16 May 1997, pp. 80-83.

[8] L. Mihet-Popa, "Wind Turbines using Induction Generators connected to the grid", Ph. D Thesis, POLITEHNICA University of Timisoara, October 2003.

[9] Lucian Mihet-Popa and Ion Boldea, "Variable speed wind turbines using induction generator connected to the grid: digital simulation versus test results", IEEE – the 9th International Conference on Optimization of Electrical and Electronic Equipment, OPTIM 2004, May 20-21, Poiana Brasov, Vol. 2, pp. 286-294;