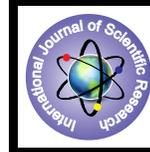


Computer Aided Design Analysis of Electrical Motor Drives for Traction Application



Engineering

KEYWORDS : DFIG, WT, Grid-fault, steady state.

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ABSTRACT

The main aim of this paper is the analysis of the doubly-fed induction generator (DFIG). For a Wind turbines (WTs) application both during steady-state operation and transient operation. In order to analyze the DFIG during transient operation both the control and the modeling of the system is of importance. Hence, the control and the modeling are also important parts of the thesis. The main contribution of this paper is dynamic and steady-state analysis of the DFIG. And in this paper an investigation of the influence of the converter's size on the energy production for a DFIG system is analyzed. A general rotor current control law is derived for the DFIG system. The grid-fault response of a DFIG wind turbine system is studied. And finally analyze, dynamically and in the steady state, two different voltage sag ride-through systems for the DFIG.

INTRODUCTION

Computer-aided design (CAD) is the use of computer systems to assist in the creation, modification, analysis, or optimization of a design. CAD software is used to increase the productivity of the designer, improve the quality of design, improve communications through documentation, and to create a database for manufacturing. CAD output is often in the form of electronic files for print, machining, or other manufacturing operations.

The Swedish Parliament adopted new energy guidelines in 1997 following the trend of moving towards an ecologically sustainable society. The energy policy decision states that the objective is to facilitate a change to an ecologically sustainable energy production system. The decision also confirmed that the 1980 and 1991 guidelines still apply, i.e., that the nuclear power production is to be phased out at a slow rate so that the need for electrical energy can be met without risking employment and welfare. The first nuclear reactor of Barsebäck was shut down 30th of November 1999. Nuclear power production shall be replaced by improving the efficiency of electricity use, conversion to renewable forms of energy and other environmentally acceptable electricity production technologies [1]. According to [2] wind power can contribute to fulfilling several of the national environmental quality objectives decided by Parliament in 1991.

Wind turbines (WTs) can either operate at fixed speed or variable speed. For a fixed-speed wind turbine the generator is directly connected to the electrical grid. For a variable-speed wind turbine the generator is controlled by power electronic equipment. There are several reasons for using variable-speed operation of wind turbines; among those are possibilities to reduce stresses of the mechanical structure, acoustic noise reduction and the possibility to control active and reactive power [2]. Most of the major wind turbine manufacturers are developing new larger wind turbines in the 3-to-5-MW range [3]. These large wind turbines are all based on variable-speed operation with pitch control using a direct-driven synchronous generator (without gearbox) or a doubly-fed induction generator (DFIG). Fixed-speed induction generators with stall control are regarded as unfeasible [3] for these large wind turbines. Today, doubly-fed induction generators are commonly used by the wind turbine industry (year 2005) for larger wind turbines [4, 5, 6, 7].

The major advantage of the doubly-fed induction generator, which has made it popular, is that the power electronic equipment only has to handle a fraction (20–30%) of the total system power [8, 9, 10]. This means that the losses in the power electronic equipment can be reduced in comparison to power electronic equipment that has to handle the total system power as for a direct-driven synchronous generator, apart from the cost saving of using a smaller converter.

Review of Related Research

According to [12] the energy production can be increased by 2–6% for a variable-speed wind turbine in comparison to a fixed-speed wind turbine, while in [13] it is stated that the in-

crease in energy can be 39%. In [14] it is shown that the gain in energy generation of the variable-speed wind turbine compared to the most simple fixed-speed wind turbine can vary between 3–28% depending on the site conditions and design parameters. Efficiency calculations of the DFIG system have been presented in several papers, for instance [15, 16, 17]. A comparison to other electrical systems for wind turbines are, however, harder to find. One exception is in [16], where Datta et al. have made a comparison of the energy capture for various WT systems. According to [16] the energy capture can be significantly increased by using a DFIG. They state an increased energy capture of a DFIG by over 20% with respect to a variable-speed system using a cage-bar induction machine and by over 60% in comparison to a fixed-speed system. One of the reasons for the various results is that the assumptions used vary from investigation to investigation. Factors such as speed control of variable-speed WTs, blade design, what kind of power that should be used as a common basis for comparison, selection of maximum speed of the WT, selected blade profile, missing facts regarding the base assumptions etc, affect the outcome of the investigations. There is thus a need to clarify what kind of energy capture gain there could be when using a DFIG WT, both compared to another variable-speed WT and towards a traditional fixed-speed WT.

In the literature there are some different methods to modify the DFIG system in order to accomplish voltage sag ride-through proposed. In [20] anti-parallel thyristors is used in the stator circuit in order to achieve a quick (within 10 ms) disconnection of the stator circuit, and thereby be able to remagnetize the generator and reconnect the stator to the grid as fast as possible. Another option proposed in [72] is to use an "active" crowbar, which can break the short circuit current in the crowbar. A third method, that has been mentioned earlier, is to use an additional converter to substitute the Y point of the stator circuit [21, 22]. In [22], Kelber has shown that such a system can effectively damp the flux oscillations caused by voltage sags. All of these systems have different dynamical performance. Moreover, the efficiency and cost of the different voltage sag ride-through system might also influence the choice of system. Therefore, when modifying the DFIG system for voltage sag ride through it is necessary to evaluate consequences for cost and efficiency. Any evaluation of different voltage sag ride-through methods for DFIG wind turbines and how they affect the efficiency is hard to find in the literature. Consequences for the efficiency is an important issue since, as mentioned earlier, one of the main advantages with the DFIG system was that losses of the power electronic equipment is reduced in comparison to a system where the power electronic equipment has to handle the total power. Moreover, it is necessary to compare the ride-through system with a system that utilizes a full-power converter, since such a system can be considered to have excellent voltage sag ride-through performance (as also will be shown in Chapter 7) [23].

WIND ENERGY SYSTEMS

In this section, properties of the wind, which are of interest in this thesis, will be described. First the wind distribution, i.e., the

probability of a certain average wind speed, will be presented. The wind distribution can be used to determine the expected value of certain quantities, e.g. produced power. Then different methods to control the aerodynamic power will be described. Finally, the aerodynamic conversion, i.e., the so-called $C_p(\lambda, \beta)$ curve, will be presented.

Energy Efficiency of Wind Turbines

This study focuses on

1. Reducing the magnetizing losses of the DFIG system
2. Influence of the converter's size on the energy production (i.e., smaller converter implies a smaller variable-speed range for the DFIG system) and finally
3. Comparison of the DFIG system to other electrical systems.

In order to make the comparison as fair as possible the base assumption used in this work is that the maximum (average) shaft torque of the wind turbine systems used should be the same. Moreover, the rated WT power used in this chapter is 2 MW.

Evaluation of the Current Control of Doubly-Fed Induction Generators

In this section the current control law derived for the DFIG in the previous chapter is analyzed with respect to eliminating the influence of the back EMF, which is dependent on the stator voltage, rotor speed, and stator flux, in the rotor current. Further, stability analysis of the system is performed for different combinations of these terms in both a stator-flux and grid-flux-oriented reference frame, for both correctly known and erroneously parameters.

Evaluation of Doubly-Fed Induction Generator Systems.

For example, the rotor current dynamics and the grid-filter current dynamics are controlled by a high-gain feedback, it is possible to force the system to have both slow and fast time scales, i.e., the system behaves like a singularly perturbed system [57]. This means, that the rotor and grid-filter current can be assumed to follow their reference values accurately.

As pointed out in the Introduction, the flux dynamics of the DFIG are strongly influenced by a pair of poorly damped poles, with an oscillating frequency close to 1 pu, i.e. close to the line frequency. If the current control loop is much faster than the flux dynamics, it is sufficient to study only the flux dynamics and put the rotor current to its reference value.

Implementation in Grid Simulation Programs

Some grid simulation programs can handle three-phase instantaneous quantities. Examples are EMTDC and Simpow. Other programs are designed to handle the voltages as phasors, and for these programs, 50-Hz oscillations in the output quantities cannot be captured, since the time step is often too large for these oscillations; an example is PSS/E. However, when handling simulations of large systems, it may not be possible to use such a short time step (about 5 μ s) as is required in order to simulate the control of the DFIG system. The suggested approach is to simply ignore the 50-Hz oscillations when the DFIG system is implemented in simulations with long time steps, as long as the disturbances are small enough not to cause the rotor to be short-circuited. For this case, a steady-state model of the DFIG is sufficient. However, if a disturbance is large enough to cause the rotor to be short-circuited, the machine will act as a standard squirrel-cage induction machine which can be adequately modeled with a fifth-order model of the induction machine [83].

As pointed out in [84, 60], the stator flux transients may be negligible from the power system stability analysis point of view. This means that if stator flux transients are negligible a steady-state model of the DFIG dynamics are sufficient as long as the rotor circuit is not short-circuited due to a too large grid disturbance.

In this section, simulations and experimental verification of the dynamic response to voltage sags of a DFIG wind turbine were presented. Simulations were carried out using a full order model and a reduced-order model. Both models produced acceptable results. Perfect correspondence with experiments was not expected since the simulations were carried out on a fictitious DFIG wind turbine. The response to symmetrical as well as unsymmetrical voltage sags was verified.

CONCLUSIONS

The electrical energy efficiency of wind turbines systems equipped with doubly-fed induction generation in comparison to other wind turbine generator system has been investigated. It was found that the energy efficiency of a doubly-fed induction generator system is a few percentage units higher compared to a system using a cage-bar induction generator, controlled by a full-power convertor. In comparison to a direct-driven permanent-magnet synchronous generator, controlled by a convertor or a two-speed generator system the difference in energy efficiency was found to be small. Moreover, the convertor losses of the doubly-fed induction generator can be reduced if the available rotor-speed range is made smaller. However, the aerodynamic capture of the wind turbine is reduced with a smaller rotor-speed range. This means that the increased aerodynamic capture that can be achieved by a larger convertor has, thus, a greater impact than the increased convertor losses. Finally, two methods to reduce the magnetizing losses of the doubly-fed induction generator system, have been investigated. It was found that the method, utilizing a Y- Δ switch in the stator circuit had the largest gain in energy, of the two investigated methods.

Voltage sag ride-through capabilities of some different variable-speed turbines have been investigated and compared. A variable-speed wind turbine with a full-power convertor system can handle voltages sags very well. Two candidates methods for improving the voltage sag ride-through capability of DFIG variable-speed wind turbines have been investigated. One of the methods still suffers, at least initially, from high fault currents, while the other method seems to have similar dynamical performance as the full-power convertor system. However, the control of the latter method is much more complicated than that of the full-power convertor system without ride through capability. The energy production cost of the full-power convertor system was found to be three percentage units higher than that of the ordinary DFIG system without ride through capability. The two DFIG candidates methods have approximately the same energy production cost, which is approximately 1.5 percentages units higher in comparison to the ordinary DFIG system.

Finally, a non-linear rotor resistance control law has been derived with the objective of minimizing the flicker contribution of a stall-controlled fixed-speed wind turbine to the grid. It has been found that the flicker contribution can be reduced with 40-80%, depending on the operating condition, with the derived control law.

Future Research

The following topics are proposed for future research.

- Development of a unified estimator for both stator-flux and grid-flux field orientation. Since the flux dynamics are poorly damped, a desired property would be a relatively good damping of the flux dynamics.
- More through dynamic, steady-state, and experimental analysis of the 3 voltage sag ride-through systems for the DFIG wind turbine. In addition, it is essential to study the hardware configuration of the voltage sag ride-through systems.
- Development of mathematical models of wind turbines with voltage sag ride-through properties. Experimental evaluation of the developed models with commercial wind turbines with voltage sag ride-through properties.
- Derivation of analytical expressions for the response of the DFIG to unsymmetrical voltage sags.

REFERENCE

- [1] Swedish energy agency, "Climate report 2001," Swedish Energy Agency, Tech. Rep. ET 29:2004, 2004. [online]. Available: [http://www.stem.se/web/biblsop.nsf/filAtkomost/ER62002.pdf/\\$FILE/ER62002.pdf?OpenElement](http://www.stem.se/web/biblsop.nsf/filAtkomost/ER62002.pdf/$FILE/ER62002.pdf?OpenElement) | [2] T. Burton, D. Shapre, N. Jenkins, and E. Bossanyi, wind energy handbook. John Wiley & sons, Ltd, 2001. | T. Ackerman and L. Soder, "An overview of wind energy-status 2002," *Renew. Sustain. Energy Rev.*, vol.6, 1-2, pp.67-128, Feb./Apr.2002. | [3] DEWIND. (2005, Jan.) the D8 series, Brochure. [online]. Available: <http://www/dewind.de/en/downloads/D8-2000-100-eng.pdf>. | [4] GE wind energy, (2005, Jan.) 3.6s offshore wind turbine. Brochure. [online] Available: http://www.gepower.com.businesses/ge_wind_energy/en/downloads/gelvrt_brochure.pdf | [5] Nordex. (2005, Jan.) N80/2500 kW N90/2300 kW. Brochure. [online]. Available: http://www.nordex-online.com/_e/online_service/download/_dateien/PB_N80_GB.pdf | <http://www.vestas.com/pdf/produkt/AktuelleBrochurer/v120/V120%20UK.pdf> | [6] L. H. Hansen, L.Helle, F. Blaabjerg, E.Ritchie, S. Munk-Nielsen, H. Bindner, P.Sorensen, and B. Bak-Jensen, "Conceptual survey of generators and power electronics for wind turbines," *Riso National Levorotatory, Roskilde, Denmark, Tech. Rep. Riso-R- 1205(EN)*, ISBN 87-550-2749-8, Dec.2001. | [7] L.Morel, H. Godfroid, A. Mirzaian, and J. Kauffmann, "Double-fed induction machine: Converter optimization and field oriented control without position sensor," *IEE Proc. Electr. Power Appl.*, vol. 145, no. 4, pp. 360-368, July 1998. | [8] L. Xu and C. Wei, "Torque and reactive power control of a doubly fed induction machine by position sensorless scheme," *IEEE Trans, Ind, Applicat.*, vol. 31, no. 3, pp. 636-642, May/June 1995. | D.Zhou and R.Spee, "Field oriented control development for brushes doubly-fed machines," in *Proc. IEEE Industry Applications Conference*, vol. 1, oct., 6-10, 1996, pp. 304-310. | [9] O. Carlson, J. Hylander, and K.Thorborg, "Survey of variable speed operation of wind turbines," in *Proc. Of European Union wind energy conference, Goteborg, Sweden, May, 20-24, 1996*, pp. 406-409. | [10] D.S. Zinger and E. Muljadi, "Annualized wind energy improvements using variable speeds," *IEEE Trans, Ind, Applicat.*, vol. 33, no.6, pp. 1444-1447. Nov/Dec. 1997. | [11] P.Mutschler and R.Hoffmann, "Comparison of wind turnbines regarding their energy generation," in *Proc. 2002 IEEE 33rd Annual IEEE Power Electronics Specialist Conference*, vol. 1, cairns, old., Australia, June, 23-27, 2002, pp. 6-11. | [12] M.G. Loannides and J.A. Tegopoulos, "Optimal efficiency slip-power recovery drive," *IEEE Trans. Energy Conversion*, vol. 3, no 2, pp. 342-348, June 1988. | [13] B. Rabelo and W. Hofmann, "Optimal active and reactive power control with the doubly-fed induction generator in the MW-Class wind-turbines," in *Proc. International Conference on Power Electronics and Drives Systems*, vol. 1, Denpasar, Indonesia, oct., 22-25 2001, pp. 53-58. | [14] Y. Tang and L. Xu, "Flixible active and reactive power control strategy for a variable speed constant frequency generating system," *IEEE Trans. Power Electron.*, vol. 10, no. 4, pp. 520-526, Sept.1993. | [15] "variable-speed wind power generation using doubly fed wound rotor induction machine-a comparison with alternative schemes," *IEEE trans energy conversion*, vol.17, no.3, pp.414-421, sept 2002. | [16] A. Ditttrich and A. Stoev, "Grid voltage falut proof doubly-fed induction generator system, in *proc. Power electronics and applications (EPE)*, Toulouse, France, Sep. 2003. | [17] J. Niiranen, "Voltage dip ride through of doubly-fed generator equipped with active crowbar," in *Proc. Nordic Wind Power Conference (NWPC)*, Goteorg, Sweden, Mar., 1-2 2004. | [18] C.R.Kelbar and W.Schumacher, "Active damping of flux oscillations in doubly-fed as machines using dynamic variataion of the system's structure," in *Proc. Power Electorincs and Applications (EPE)*, Graz, Austria, Aug., 27-29 2001. | [19] C.R. Kelber, "Aktive damping der doppelt-gepeisten Drehstrommaschine," Ph.D. dissertation, Technihen University carolo-Wilhelmina, 2000, (in German). | [20] R. Ottersten, A. Petersson, and K.Pietilainen, "Voltages sag response of PWM rectifiers for variable-speed wind turbines," in *Proc. IEEE Nordic Workshop on Power and Industrial Electronics (NORPie' 2004)*, Trondheim, Norway, June, 14-16 2004. | [21] J.G. Nielsen, M. Newman, H. Nielsen, and E.Blaabjerg, "Control and testing of a dynamic voltage restorer (DVR) at medium voltage level," *IEEE Trans. Power Electron.*, vol.19, no.3, pp.806-813, May 2004. | [22] A. Lasson and P. Lundberg, "Trefas sjalvommuterade stromriktare anslutna tillenatet-En inledande studie," *Charmers University of Technology, Goteborg, Sweden, Tech. Rep.*, 1990. | [23] PSS/E-Introduction to Dynamic Simulation, Manula, Power Technologies, Inc., Schenectady, NY, USA, 2001. |