2012

Permanent Magnet Generator Design and Control for Large Wind Turbines

Xu Yang
University of Nebraska-Lincoln, yangxty@gmail.com

Dean Patterson
University of Nebraska - Lincoln, patterson@ieee.org

Jerry L. Hudgins
University of Nebraska-Lincoln, jhudgins2@unl.edu

IEEE Power Electronics and Machines in Wind Applications (PEMWA)
Denver, Coronado, July 16-18, 2012; DOI: 10.1109/PEMWA.2012.6316367

Permanent Magnet Generator Design and Control for Large Wind Turbines

Xu Yang, Dean Patterson, Jerry Hudgins
Department of Electrical Engineering
University of Nebraska-Lincoln
Lincoln, NE 68588-0511
Email: xu.yang@huskers.unl.edu, patterson@ieee.org, jhudgins2@unl.edu

***Abstract*—Direct drive permanent magnet generators(PMGs) are increasingly capturing the global wind market in large onshore and offshore applications. The aim of this paper is to provide a quick overview of permanent magnet generator design and related control issues for large wind turbines. Generator systems commonly used in wind turbines, the permanent magnet generator types, and control methods are reviewed in the paper. The current commercial PMG wind turbine on market is surveyed. The design of a 5 MW axial flux permanent magnet (AFPM) generator for large wind turbines is discussed and presented in detail.**

***Index Terms*—Direct drive, permanent magnet generator, axial flux permanent magnet generator.**

I. Introduction

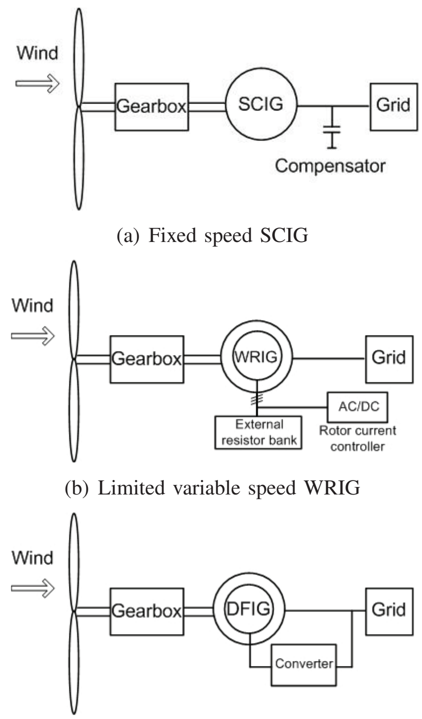
During the past few years wind energy had been a very fast growing market worldwide. According to the World Wind Energy Association (WWEA), the total world market for wind turbines in 2011 reached 42 gigawatts, preceded 37.6 gigawatts in 2010 [1]. The U.S. wind industry installed a total of 6810 megawatts (MW) during 2011, a 31% increase over 2010 [2]. Various generator types and control techniques have been presented to maximize wind capture, reduce costs and improve reliability. The doubly fed induction generator (DFIG) with a three-stage gearbox is the most common configuration at present. Permanent magnet generators (PMGs) are capturing more attention. They are widely used in small wind turbines, and increasingly in large onshore and offshore wind turbines. A one/two stage gearbox or even a direct drive train type can be used with them. Direct drive types are used for their reduced part count, ease of maintenance, high reliability and reduced power loss. According to a global market report [3], direct drive technology captured approximately 17.4% share in the global wind turbine market for 2010, and is expected to capture 24.3% of the overall wind turbine installations by 2016.

This paper reviews some generator systems commonly used in wind turbines, both for current commercial markets as well as future trends. Permanent magnet generators in wind turbines and control techniques are reviewed. A detailed design for a 5MW AFPM generator for large wind turbines is presented.

II. Review of Generator Configurations in Wind Energy Conversion Systems

Wind energy conversion configurations can be classified as fixed speed or variable speed, geared or direct drive, and so on. In this section, topologies with different types of generators will be summarized and future trends analyzed.

A. Asynchronous Generators



(a) Fixed speed SCIG

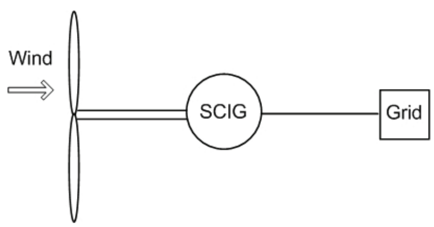
(b) Limited variable speed WRIG

(c) Variable speed DFIG

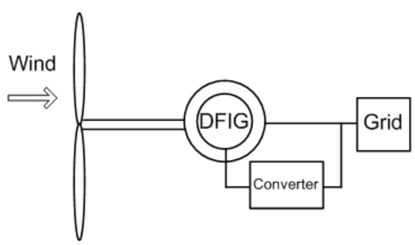
Fig. 1. Wind turbine system with asynchronous generators

1) Induction generator(IG) and double fed induction generator(DFIG): Most early wind turbines were designed used a squirrel cage induction generator (SCIG) with close to fixed speed and directly connected to the grid, as was used during the 1980s and 1990s in stall-regulated wind systems [4] as in Fig.1(a). It has been phased out due to several disadvantages, such as non-controllable speed, gearbox complexity, and excitation current from the grid. Later in the mid-1990s, the ”Optislip” concept, which uses wound rotor induction generator (WRIG) with an external resistor bank connected to the rotor and power electronic circuitry to implement rotor current control as in Fig.1.(b), allowing a limited variable speed, was applied [5]. Currently, the well-known DFIG as in Fig.1.(c), has become the industry standard for todays on-shore wind turbines. It is a variable speed wind turbine system with a wound rotor induction generator and a partial scale converter, which controls the rotor speed. A multistage gearbox, normally a three-stage gearbox, is used in the drive train.

2) Future possible topology: Although the current DFIG technology is well developed and it is a very cost effective solution, it has some drawbacks. The use of a gearbox increases the weight of a nacelle,with more power loss and increased costs, especially in the offshore applications when the power rating goes up. As indicated in [6], the losses in the gearbox represent 65% of the total power loss in the generation system. Thus, a direct drive topology is preferred, although most researchers do not commonly consider induction generators for direct drive applications. In [7], the feasibility of a direct drive SCIG design was studied as shown in Fig.2(a). In [8], the feasibility of a 10MW multi-pole DFIG design was found to be borderline as in Fig.2(b). A small scale 2.5kW direct drive induction generator capable of being directly connected to the grid has been commercialized [9].



(a) Direct drive SCIG wind turbine system



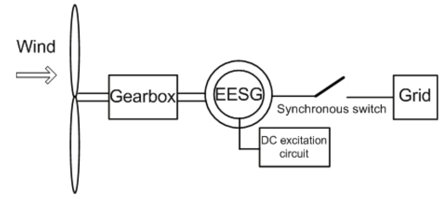
(b) Direct drive DFIG wind turbine system

Fig. 2. Direct drive wind turbine system with asynchronous generators

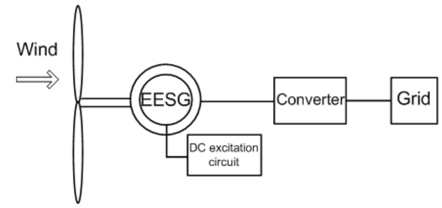
B. Synchronous Generators

Synchronous generators can be classified as electrical excited synchronous generators (EESGs) and permanent magnet generators(PMGs).

1) Electrical excited synchronous generator: The EESG does not need the permanent magnets whose production requires rare earth materials, such as neodymium, whose extraction can cause environmental damage. Fig.3(a) shows a fixed speed wind turbine with a gearbox in which the EESG is directly connected to the grid through a synchronous switch. It eliminates the need for power electronics conversion since the generator voltage can be regulated to 4.16kV/13.8kV. Compared to Fig.1(a), it has improved efficiency. Fig.3 (b) shows the direct drive EESG system with full scale converters. The successful manufacturers are Enercon and Dewind. The largest capacity in use is up to 7.5MW in the Enercon E-126/7.5MW wind turbine.



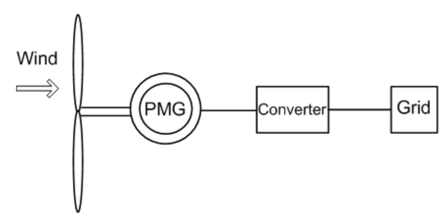
(a) Fixed speed EESG wind turbine system with gearbox



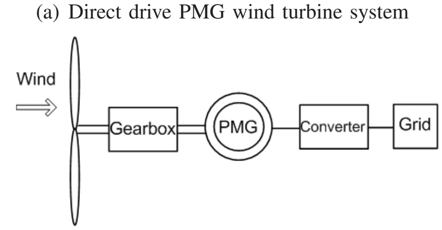
(b) Direct drive EESG wind turbine system

Fig. 3. Wind turbine system with EESG

2) Permanent magnet generator (PMG): Compared to the EESG, the PMG has several advantages: high efficiency with the elimination of field loss, and it is small and light, to list a few. They are not only preferred in small scale wind turbines but also in large MW applications. The commercialized PMG wind turbines to date were surveyed and summarized in Table I. Many companies have ambitious plans for large power rating PMGs. Alstom, Nordex, and Siemens expect their 6 MW turbines to be in serial production in 2014. However, as the rating goes up to 7-10 MW in direct drive wind turbines, the generator grows rapidly larger and heavier, thus a single or two-stage gearbox is favored to provide a smaller and lighter generator. This gearbox solution is shown in Fig.4.(b). The Vestas V164-7.0MW applies the single gearbox system, with serial production planned for 2015.



(a) Direct drive PMG wind turbine system



(b) PMG wind turbine system with gearbox

Fig. 4. Wind turbine system with PMG

TABLE I
COMMERCIAL WIND TURBINE WITH SYNCHRONOUS MACHINE(LARGE THAN 1MW)

Manufacture, Country	Power level (MW)	Generator type	Drivetrain type	Rotor speed(rpm)	Rotor diameter(m)	Generator voltage(v)	Model
Alstom, USA	6.0	PMG	Direct drive	4-11.5	150	-	-
AMSC, USA	10	HTS generator	Direct drive	10	190	-	SeaTitan 10MW
Dewind, Germany	2	EESG	Gearbox	1500/1800	93/80	4.16-13.8k	DeWind D9.2/D8.2
	2	PMG	Gearbox	1700	93	690	DeWind D9.1
EWT,Netherland	2.0	PMG	Direct drive	7-18	90/96	-	DIRECTWIND90/96
Enercon, Germany	7.5	EESG	Direct drive	5-11.7	127	-	E126/7.5MW
	3	EESG	Direct drive	4-14.5	101	-	E-101/3MW
	2	EESG	Direct drive	6-17.5	82	-	E-82 E2/MW
Gamesa,Spain	4.5	PMG	Gearbox	448	128/136	690	G128/G136-4.5MW
GE,USA	4.1	PMG	Direct drive	8.0-20	113	690	GE 4.1-113
Leitwind, Italy	3.0	PMG	Direct drive	6-14.4	101	690	LTW101/3000
	2.0/1.7	PMG	Direct drive	20.8	70.1	690	LTW70-2000(1700)
	1.8/1.5	PMG	Direct drive	17.8	80.3/76.6	675/640	LTW80-1800(77-1500)
Nordex,	6	PMG	Direct drive	3.5-11.9	150	3.3k/4.5k	NordexN150
NPS, USA	2.3	PMG	Direct drive	-	93	-	NPS2.3
Siemens Germany	2.3	PMG	Direct drive	6-13	113	690	SWT-2.3-113
	3	PMG	Direct drive	6-16	101	690	SWT-3.0-101
	6	PMG	Direct drive	5-11	154	690	SWT-6.0-154
The Switch, Finland	4.25	PMG	Direct drive	16	-	690	PMG4250-16
Vestas, Denmark	7.0	PMG	Gearbox	4.8-12.1	164	-	V164-7.0MW
Vensys, Germany	1.5	PMG	Direct drive	9-19	70/76/82	690	Vensys 70/77/82
	2.5	PMG	Direct drive	8.5-16	90/99.8	690	Vensys90/100

3) Other concepts: A high temperature superconducting(HTS) generator with reduced power loss is being considered for future high power ratings [10]. AMSC is developing a 10 MW HTS generator. New drive train concepts, such as magnetic gears, or pseudo direct drive (PDD) configurations, are under development, but are not yet commercially available.

III. PERMANENT MAGNET GENERATOR DESIGN IN WIND TURBINES

A. Review of Permanent Magnet Generator Types in Wind Turbines

PM generators can be classified by different concepts. Here they are classified into three concepts: radial flux permanent magnet (RFPM) machines, axial flux permanent magnet (AFPM) machines, and transverse flux permanent magnet (TFPM) machines [11]. This paper focuses on the first two types.

Radial flux permanent machines, in which the magnetic flux crosses the air gap in the radial direction, are widely used in commercial wind turbines. The RFPM machine can be categorized into surface-mounted PM and flux-concentrated PM machines. Most RFPMs have the conventional (inner rotor) type; however the inverted (outer rotor RFPM), where the rotor spins on the outside of the stator, is quite common . One of the commercialized products is the Siemens direct drive 3.0 MW wind turbine (SWT-3.0-101).

Axial flux permanent magnet machines have gained much attention for their disc-type structure. Compared to RFPMs, AFPMs have higher torque volume density and shorter axial length [12]. Researchers have investigated them for small wind turbine systems [13]. However the feasibility of the AFPM for large MW has not been investigated. Thus the design of a 5MW AFPM is detailed in the following section.

B. Design Consideration for PMGs in Large Direct Drive Wind Turbines

1) Design procedure of a 5 MW AFPM generator : A single sided AFPM was considered, although there are debates about the best format for axial flux machines [14]. For a 5 MW machine, the rotor typically operates at 5-15 rpm as in Table 1. Here, the rated speed selected is 12 rpm, the rated torque will be 3.98 MNm.

First, the air gap shear stress σ, which is the tangential force per unit of swept air gap surface area, needs to be determined. In AFPM [15],

$$\sigma = \frac{T}{R_{av} \cdot A_{ag}} = B_m \cdot A_e \tag{1}$$

R_{av} is the average radius, A_{ag} equals to $\pi(R_o^2 - R_i^2)$, which is the airgap surface area. B_m is the magnetic loading, and A_e is the electric loading.

In industrial air cooled machines, the air gap shear stress varies between 15-50kPa [16]–[18]. Here, it is chosen to be 45kPa.

The magnetic loading, B_m is limited by the remanent flux density the magnets can achieve. The average flux densities

TABLE II
DIMENSIONS OF A 5MW AFPM GENERATOR

Generator dimensions	
Number of poles(2p)	500
Number of slots(Q)	750
Stator outer radius(m)	6.5
Stator inner radius(m)	6.15
Stator slot depth(mm)	50
Stator slot width(mm)	20
Slot filling factor	0.6
Stator yoke thickness(mm)	30
Remnant flux density of NdFeB35(T)	1.32
Magnet pole arc/pole pitch	0.85
Pole pitch(mm)	79.5
Magnet thickness(mm)	12
Air gap thickness(mm)	6
Rotor yoke thickness(mm)	20
Weight(tons)	
Steel	27.3
Magnet	1.1
Copper	1.67

in the air gap are in the range of 1T. Here, B_m is chosen as 0.8T. Thus, the electric loading is 56.5kA/m.

The electric loading relates to the current density in the slots. There are no theoretical limits. However, higher current density will dramatically increase Joule heating loss. In air cooled machine, current density is normally 5-10A/mm^2. Here, 5A/mm^2 has been chosen.

Pole numbers 2p was chosen as 500, thus the electrical frequency at 12 rpm is 50 Hz, which is a reasonable value for limiting the core loss. Slot number Q was chosen as 750 for local minima rotor losses at Q/2p=1.5 in non-overlapped windings (NOW) machine according to [19].

The machine dimensions based on the above principles are listed in Table II.

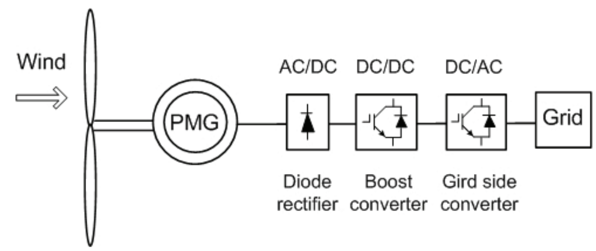
IV. BRIEF REVIEW OF CONTROL OF PMG IN WIND TURBINES

A. Control Variables in Wind Energy Conversion System

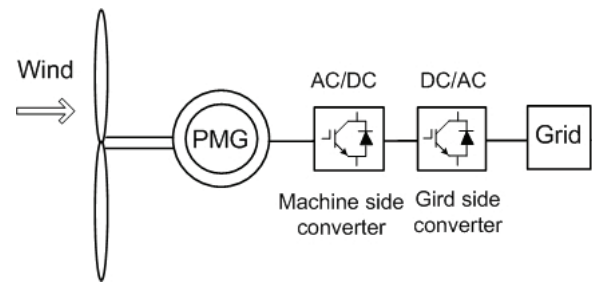
There are three control variables in the wind turbine system: pitch angle, yaw angle, which is often a forgotten factor [20] and generator speed. In low and medium wind speed, the aim of control is to maximize the output power from the wind turbine by adjusting the generator speed and yaw angle. The function of yaw control is to orient the wind turbine so that it perpendicularly faces the wind stream, to reduce power loss. In high wind speed, the pitch angle will be adjusted to keep the output power constant at the nominal value. Since the first two variables are mechanical factors, the control of generators will be focused on here.

B. Converter Topologies and Control Methods of PMG in Wind Turbines

1) PMG with diode rectifier: Different topologies are investigated for various PMG wind turbines [21]. Since a PMG does not need reactive power, a diode rectifier with a boost converter and inverter can be used for cost effective solutions with more reliability compared with PWM rectifiers [22], as shown in Fig.5.(a). This system is used industrially today not only in small wind turbines but also in large wind turbines. The generator power is controlled through the current control in the boost converter.



(a) PMG with diode recitifer and boost converter



(b) PMG with back to back converter

Fig. 5. Control topologies of PMG wind turbine

2) PMG with back to back converter: However, a back to back converter, as shown in Fig.5.(b) is generally applied to provide flexible control as showed in figure. As in [23] the machine side converter is used to control the power flow from the generator, while the grid side converter maintains the dc link voltage and control the reactive power to the grid.

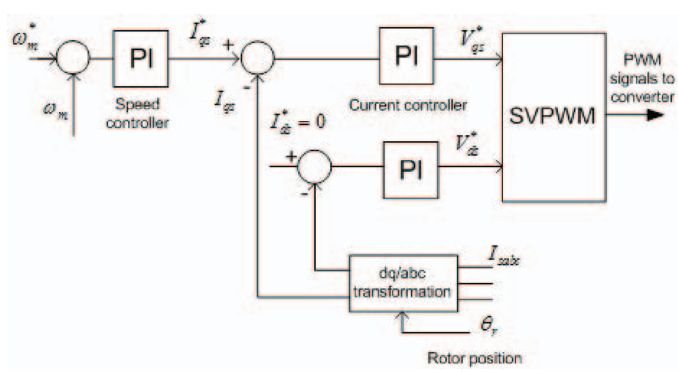


Fig. 6. Field oriented control (FOC) diagram

For the machine side converter, the control methods can be generally categorized into two: field oriented control (FOC) and direct torque control (DTC). The most widely used is FOC, which uses current control loops in the synchronous reference frame as in Fig.. DTC eliminates the current controller and coordination transformation, in which the torque and stator flux linkage is controlled directly and independently. The torque and stator flux linkage is estimated through the stator voltage and current.The errors are limited in the hysteresis bands. Figure.7(b) shows the control diagram of conventional DTC. Another DTC based control method, DTC-SVM is presented in [24]

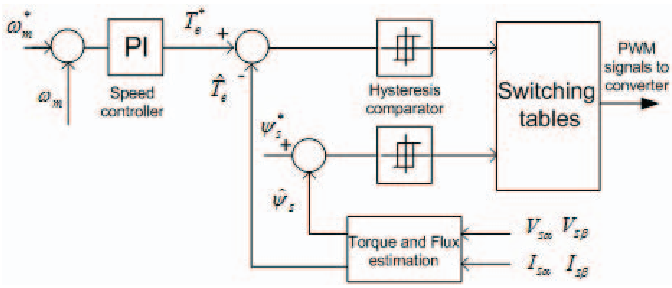


Fig. 7. [Direct torque control (DTC) diagram

Through the comparative analysis [25], it could be shown that FOC achieves a lower current harmonics, while DTC performs a faster torque response. The selection of which method will be determined according to situations.

V. Conclusion

This paper provides a quick review of common wind energy conversion systems, focusing on permanent generator design and control issues for large wind turbines. A design for 5 MW AFPM generator is presented. Further studies about generator design and control will be implemented in the future.

References

[1] [Online]. Available: http://www.researchandmarkets.com/

[2] [Online]. Available: http://www.awea.org/

[3] [Online]. Available: http://www.researchandmarkets.com

[4] H. Li and Z. Chen, "Overview of different wind generator systems and their comparisons," *Renewable Power Generation, IET*, vol. 2, no. 2, pp. 123 –138, June 2008.

[5] M. Khadraoui and M. Elleuch, "Comparison between optislip and fixed speed wind energy conversion systems," in *Systems, Signals and Devices, 2008. IEEE SSD 2008. 5th International Multi-Conference on*, July 2008, pp. 1 –6.

[6] H. Polinder, F. van der Pijl, G.-J. de Vilder, and P. Tavner, "Comparison of direct-drive and geared generator concepts for wind turbines," in *Electric Machines and Drives, 2005 IEEE International Conference on*, May 2005, pp. 543 –550.

[7] M. Henriksen and B. Jensen, "Induction generators for direct-drive wind turbines," in *Electric Machines Drives Conference (IEMDC), 2011 IEEE International*, May 2011, pp. 1125 –1130.

[8] V. Delli Colli, F. Marignetti, and C. Attaianese, "Analytical and multiphysics approach to the optimal design of a 10-mw dfig for direct-drive wind turbines," *Industrial Electronics, IEEE Transactions on*, vol. 59, no. 7, pp. 2791 –2799, July 2012.

[9] [Online]. Available: http://www.allearthrenewables.com

[10] C. Lewis and J. Muller, "A direct drive wind turbine hts generator," in *Power Engineering Society General Meeting, 2007. IEEE*, June 2007, pp. 1 –8.

[11] D. je Bang, H. P. Under, G. Shrestha, and J. Ferreira, "Promising direct-drive generator system for large wind turbines," in *Wind Power to the Grid - EPE Wind Energy Chapter 1st Seminar, 2008. EPE-WECS 2008*, March 2008, pp. 1 –10.

[12] D. Patterson, J. Colton, B. Mularcik, B. Kennedy, S. Camilleri, and R. Rohoza, "A comparison of radial and axial flux structures in electrical machines," in *Electric Machines and Drives Conference, 2009. IEMDC '09. IEEE International*, May 2009, pp. 1029 –1035.

[13] A. Ferreira, A. Silva, and A. Costa, "Prototype of an axial flux permanent magnet generator for wind energy systems applications," in *Power Electronics and Applications, 2007 European Conference on*, Sept. 2007, pp. 1 –9.

[14] D. Patterson, C. Brice, R. Dougal, and D. Kovuri, "The "goodness" of small contemporary permanent magnet electric machines," in *Electric Machines and Drives Conference, 2003. IEMDC'03. IEEE International*, vol. 2, June 2003, pp. 1195 – 1200 vol.2.

[15] J. Colton, "Design of an integrated starter-alternator for a series hybrid electric vehicle: A case study in axial flux permanent magnet machine design," Ph.D. dissertation, University of Nebraska Lincoln, Lincoln, NE, 2010.

[16] J. Hendershot and T. Miller, *The Design of brushless permanent-magnet machines*. Motor Design Books LLC, 2010.

[17] A. Grauers and P. Kasinathan, "Force density limits in low-speed pm machines due to temperature and reactance," *Energy Conversion, IEEE Transactions on*, vol. 19, no. 3, pp. 518 – 525, Sept. 2004.

[18] P. Kasinathan, A. Grauers, and E. Hamdi, "Force density limits in low-speed permanent-magnet machines due to saturation," *Energy Conversion, IEEE Transactions on*, vol. 20, no. 1, pp. 37 – 44, March 2005.

[19] N. Bianchi, S. Bolognani, and E. Fornasiero, "An overview of rotor losses determination in three-phase fractional-slot pm machines," *Industry Applications, IEEE Transactions on*, vol. 46, no. 6, pp. 2338 –2345, Nov.-Dec. 2010.

[20] M. Priyavadan, D. Elizabeth, Andrew, and etc. (2012) Yaw control: the forgotten controls problem. [Online]. Available: http://www.catchthewindinc.com/

[21] F. Blaabjerg, F. Iov, Z. Chen, and K. Ma, "Power electronics and controls for wind turbine systems," in *Energy Conference and Exhibition (EnergyCon), 2010 IEEE International*, Dec. 2010, pp. 333 –344.

[22] V. Yaramasu and B. Wu, "Three-level boost converter based medium voltage megawatt pmsg wind energy conversion systems," in *Energy Conversion Congress and Exposition (ECCE), 2011 IEEE*, Sept. 2011, pp. 561 –567.

[23] X. Yang, X. Gong, and W. Qiao, "Mechanical sensorless maximum power tracking control for direct-drive pmsg wind turbines," in *Energy Conversion Congress and Exposition (ECCE), 2010 IEEE*, Sept. 2010, pp. 4091 –4098.

[24] M. elechowski, "Space vector modulated direct torque controlled (dtc svm) inverter fed induction motor drive," Ph.D. dissertation, Warszaw University of Technology, 2005.

[25] F. Nuno, E. Jorge, and C. Antonio. (2012) A comparative analysis of pmsg drives based on vector control and direct control techniques for wind turbine applications. [Online]. Available: http://pe.org.pl/articles/2012/1a/39.pdf