Proceedings of the Seventh IASTED International Conference
POWER AND ENERGY SYSTEMS
August 29–31, 2007, Palma de Mallorca, Spain
ISBN Hardcopy: 978-0-88986-689-8 / CD: 978-0-88986-690-4

DESIGN AND OPTIMIZATION OF 8MW DIRECTLY DRIVEN SURFACE MOUNTED PERMANENT MAGNET WIND GENERATORS

Wang Shanming
Institute of Power Electronics and Electrical Machine System
State Key Lab of Power Systems
Department of Electrical Engineering
Tsinghua University, Beijing, China
Wangsm96@mails.tsinghua.edu.cn

Uwe Schaefer
Institute of Energy and Automation
Department of Electrical Drive Technology
University of Technology, Berlin, Germany
Uwe.Schaefer@iee.TU-Berlin.DE

ABSTRACT
Recently more and more attentions have paid to the directly driven permanent magnet wind generators, and the capacity of wind generator becomes larger and larger. It is reasonable to believe that the next step would reach more than 8 MW, especially for an offshore turbine. In order to decide whether or not the directly driven permanent magnet wind generator is suitable for the new wind turbine system, the 8MW directly driven surface mounted permanent magnet synchronous wind generator is designed in this paper. And the detail design procedure is introduced. In order to optimize the performance, volume and weight, the EMF, armature reaction reactance, and different parts of leakage reactance are analyzed and the optimization method is obtained. At last the design results of 8MW generator are given.

KEY WORDS
Wind generator, permanent magnet, directly driven, design and optimization

1. Introduction

Today the economic growth and social development more and more rely on the energy. Wind energy is an environmental friendly and renewable source, and its utilization can help in reducing the dependency on fossil fuels with limit reservation. An average annual growth rate of more than 30% in the installed wind power capacity has been observed during the last few years[1], which is helped by the environmental policies and tax incentives of the various national governments. The more important reason is the decreasing production cost of wind energy caused by the remarkable development of wind power technology.
China has become one of the major markets of wind energy, after the European, USA and India. Now the total capacity of wind turbine reached 1.27 million kW. According to the long term industrial layout issued by Chinese government, the total capacity of wind generators is arranged to reach 5 million kW by 2010, 10 million kW by 2015 and 20 million kW by 2020, which is a great opportunity and challenge for Chinese and foreign companies.
In recent years more and more attentions have paid to the configuration of the direct-drive synchronous generator with power electronic converter because of its many advantages[2-9]: reduced overall size, high overall efficiency and reliability, low audible noise, low installation and maintenance cost, a flexible control method and quick response to wind fluctuations and load variation. But the directly driven generator is a high torque machine, so the mass of electrical machines would be many times heavier and more expensive than high speed machines.
The developments and applications of permanent magnet material make the electrical machine with high efficiency, high power density and simple rotor structure[10-12]. So the directly driven permanent magnet generator is very attractive to either the electrical engineers or the manufacture companies. Table 1 lists some information of the manufactured permanent magnet wind generators and electrical excited wind generators. The rated power of directly driven permanent magnet wind generator reaches 3.4MW, while the Enercon electrical excited generator is 6MW. This upscaling would continue to reach more than 8 MW, especially for an offshore turbine.
In this paper the 8MW directly driven surface mounted permanent magnet synchronous wind generator is designed. The performance, volume and weight of generators are used to decide whether or not it is suitable for the new wind turbine system. In order to optimize the performance, volume and weight, the EMF, armature reaction reactance, and different parts of leakage reactance are analyzed in detail and the optimization method is obtained. At last the design results of 8MW generator are given.

2. Rated data of permanent magnet wind generator

Fig 1 shows the power curve and rational speed of an 8MW low speed permanent magnet wind generator, which is only the simplified up-scaling from Multibrid M5000[13].

When the wind speed is greater than 12m/s, the output power keeps at 8MW and the rotation speed of rotor 11.7rpm. Until the wind speed reaches 25m/s, the turbine would be cut out.

3. Control method

The wind generator is connected to the grid through converter. The AC power from the generator is rectified to DC power by the controlled rectifier, and then inverted to AC power with the same frequency as the grid. Through the controlled rectifier, not only the AC voltage on the terminals of generator can be adjusted, but also the phase of current can be regulated relative to the phase of voltage. So the generator can send out reactive power, as well as absorb reactive power from the controlled rectifier.

The control method of the rectifier is shown in Fig 2, where the phase of current is in phase with the voltage. Therefore for the same output power, the current is minimal, which has many advantages: the area of stator conductor is minimal, the copper loss is minimal, and the current and capacity of rectifier is minimal.

Using this control method, the EMF of stator winding must be $E_q = \sqrt{U^2 + (IX_s)^2}$, like the normal excitation of the electrical excited generator. If the EMF is higher, the generator would send out reactive power, like the over excitation condition. If the EMF is lower, the generator would absorb reactive power, like the under excitation condition. It is difficult to make exactly $E_q = \sqrt{U^2 + (IX_s)^2}$, so the power factor(PF) would be controlled greater than 0.95(lag or lead). Therefore the rated data of the 8MW generator is shown in Table 2.

Table 1 Data of Manufactured wind generators

Company	permanent magnet(PM) or electrical excitation(EE)	Model	Rated Power	Directly driven or not
ScanWind	PM	3000 DL	3.4MW	Y
Zephyros	PM	Z72	2MW	Y
Lagerwey	PM	LW72	2MW	Y
Mitsubishi	PM	MWT-s2000	2MW	Y
PERMA Power Energy	PM(outer rotor)	Vensys62	1.2MW	Y
JEUMONT	PM(Axial airgap)	J48	750kW	Y
Enercon	EE	E112	6MW	Y
mtorres	EE	TWT1670	1.65MW	Y
ALSTOM	PM	Multibrid 5000	5.26MW	N
GE	PM		3MW	N
WinWind	PM	WWD-3	3MW	N

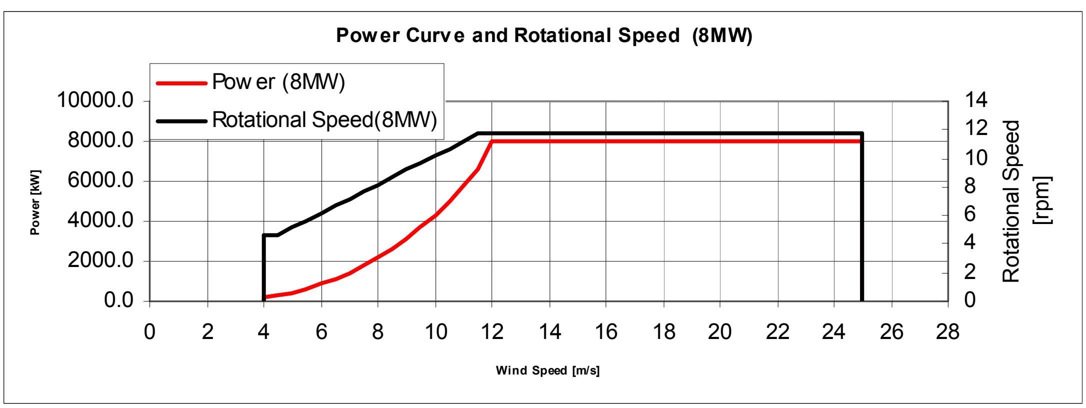

Fig 1 Power curve and rotational speed of 8MW wind generator

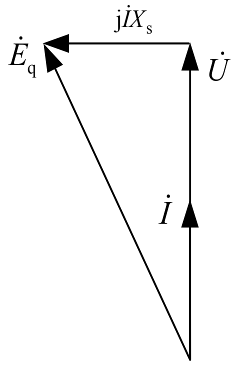

Fig 2 Phasor diagram of control method of rectifier

Table 2 Rated data of 8MW permanent magnet wind generator

Rated Power	8 MW
Rated Line Voltage	3000 V
Phase Number	3
Rated Power Factor	1.0 (>=0.95)
Rated Current	1540 A
Rated Speed	11.7 rpm
Connection	Y

4. Design of surface mounted permanent magnet wind generators

At the beginning of design procedure, many key quantities must be determined, shown as below.

4.1 Airgap shear stress σ

Because the speed of directly driven generator is low, e.g. the speed is below 20rpm for the 8MW generator, the torque is rather larger than that of high speed generator and therefore the volume and weight of low speed generator would be larger too. The volume, weight and cost are the most critical factors for the application of the low speed permanent magnet wind generator.

The airgap shear stress is one of the effective measures of power density for electric machines. The airgap shear stress is the force per unit area on the rotor surface due to the torque, and is defined as:

$$\sigma = \frac{2T_N}{\pi D^2 l}$$

where σ is the airgap shear stress, T_N is the torque, D is the rotor outer diameter, and l is the rotor core length.

Table 3 lists the airgap shear stress of some different typical machines, where the airgap shear stress can reach as high as 120 kN/m^2. Anyway the airgap shear stress is related to the magnetic and electric loads, and the temperature rise and cooling method of machine. There is no detail information about the cooling system of those machines. For the directly driven permanent magnet wind generator, the airgap shear stress is set between 50~75 kN/m^2.

Table 3 The airgap shear stress of typical machines[14]

Electric machine	airgap shear stress(kN/m^2)
Standard large industrial induction motor	15
High performance 1500rpm induction motor	35
Low speed mill induction motor	45
Advanced induction motor	100
Permanent Magnet Motor	120
High temperature superconducting motor, 25MW at 120 rpm	340

4.2 The ratio of length to diameter ρ

When a certain airgap shear stress is chosen, the volume of rotor is fixed. But the length and the diameter of the rotor can be adjusted to obtain different shape generator with different parameters. The ratio ρ is defined as: $\rho = l/D$. If the generator is long, the diameter would be small. Different combinations have different effects: the slot leakage inductance is proportional to the core length, so the longer generator would has larger slot leakage inductance; the end winding leakage inductance is proportional to the diameter and the pitch of the coils, but has nothing to do with the length, so the larger diameter leads to large end winding inductance; at the same time the large diameter allows more pole number. And also the ratio ρ would influence the weight and cost of effective materials. For the low speed generator, the typical ratio ρ is 0.5.

4.3 The pole pair number p

If the pole pair number is high, the flux per pole would small, which leads to the decrease of the thickness of the stator and rotor yoke. It makes the generator like a ring, Enercon company called it "Ring generator". One paper researched on the optimization of low speed generator and suggested that the pole pitch of 68~100mm would make the performance better.

4.4 The slot number per pole per phase q

Because the pole pitch is small, narrow tooth and deep and thin slot would result from the greater slot number per pole per phase. The slot number per pole per phase q is always less than 2 for the low speed generator.

4.5 The parallel branch number a

The mechanical error and any asymmetry of the structure would lead to the circulating current between different branches. In order to avoid the circulating current, the parallel branch number a is 1.

4.6 The airgap length δ

From the electrical view, the shorter airgap length, the better. But the shorter airgap length would lead mechanical unstable. The airgap length is calculated as $\delta = \frac{D}{1600} + 0.6$. If the band is used to protect the magnet for the surface mounted permanent magnet wind generator, additional 3mm would be added.

4.7 Height and width of permanent magnet

Higher permanent magnet can cause higher flux density and wider permanent magnet can increase the flux per pole. Usually the height of permanent magnet is usually 5 times to the length of airgap, which makes the airgap flux density is 83% of the residence flux density of permanent magnet. Additionally, the height of permanent magnet must be enough to resist the demagnetization effect of stator current under normal and fault conditions. The width would be as narrow as possible to satisfy the performance requirements.

4.8 Current density J

On one hand, high current density would make the copper area decrease, consequently the slot area is small and the depth of slot would be decreased too. So the slot leakage inductance, which is a large component of synchronous inductance, can be decreased.
On the other hand, high current density would result in the increasing of winding resistance, which makes the efficiency decrease.
So the current density would be the compromise between slot leakage inductance and resistance. In this project the current density is set below 4 A/mm^2 .

4.9 Slot shape

The parallel slot is chosen, the width of which is equal to the half of the tooth pitch. The depth of slot is calculated by the area of conductor. The slot fill factor, which is defined as the ratio of the copper area to the total area of slot, is set as about 0.5.
After these quantities were decided, the parameters and performance are calculated and analyzed by use of the software SPEED in this paper.

5. Optimization method

The design results show that when the rated power 8MW is reached, the power factor is easy to be quite low, such as 0.909. To increase the power factor, the most direct way is to increase the EMF, like the electrical excited generator. But there is no field current can be regulated for the permanent magnet generator, and the increase of the EMF implies the increase of the volume of permanent magnet, which makes the generator not cost effective.
Another effective way to increase the power factor is to decrease the reactances, including the armature reaction reactance, the slot leakage reactance, the end winding leakage reactance and the differential leakage reactance. From the calculation results of SPEED, it can be seen that the leakage reactances play important roles in the total synchronous reactance, of which more than 50% is the leakage reactances.
So the design of generator becomes an optimization problem, which requires the reactances smaller, but the EMF higher at the same time. Therefore the EMF, the armature reaction reactance, the slot leakage reactance, the end winding leakage reactance and the differential leakage reactance, are analyzed in detail.

5.1 EMF

From the equations, $f = \frac{pn}{60}$, $N_p = \frac{2pqN_k}{a}$, $\tau = \frac{\pi D_i}{2p}$, $\phi_1 = B_{1av} l \tau = B_{1av} l \frac{\pi D_i}{2p}$, the EMF of phase winding can be gotten as,

$$E_q = 4.44 f N_p k_{dp1} \phi_1 = 4.44 \frac{pn}{60} \frac{2pqN_k}{a} k_{dp1} B_{1av} l \frac{\pi D_i}{2p}$$

$$= \frac{4.44\pi^2}{2 \times 60} \frac{nqN_k k_{dp1}}{a} \frac{D_i^2 l}{\tau} B_{1av}$$

where N_p is phase turn number, ϕ_1 is the per pole flux, B_{1av} is the average of flux density.

Considering $D^2 l \approx \frac{60 P_N}{\sigma \pi^2 n}$, then

$$E_q \approx \frac{4.44}{2} \frac{qN_k k_{dp1}}{a} \frac{P_N}{\tau\sigma} B_{1av}$$

So, $E_q \propto \frac{qN_k k_{dp1}}{a} \frac{1}{\tau\sigma} B_{1av}$, the EMF is proportional to the $\frac{qN_k k_{dp1}}{a}$, and is inversely proportional to the pole pitch τ and the airgap shear stress σ .

5.2 Armature reaction reactance

For the non-salient generator, the armature reaction reactance is

$$X_a = 6f\frac{\mu_0 D_i l}{p^2\delta'}(N_p k_{dp1})^2 = \frac{6pn}{60}\frac{\mu_0 D_i l}{p^2\delta'}(\frac{2pqN_k k_{dp1}}{a})^2$$

$$= \frac{6\times 2\mu_0\pi}{60}\frac{nq^2N_k^2k_{dp1}^2}{a^2}\frac{D_i^2 l}{\tau\delta'}$$

where $\delta' = k_\delta\delta + h_M$ is the equivalent airgap length considering the effect of permanent magnet.

Considering $D^2 l \approx \frac{60P_N}{\sigma\pi^2 n}$, then

$$X_a = \frac{6\times 2\mu_0}{\pi}\frac{q^2N_k^2k_{dp1}^2}{a^2}\frac{P_N}{\tau\delta'\sigma}$$

So, $X_a \propto \frac{q^2N_k^2k_{dp1}^2}{a^2}\frac{1}{\tau\delta'\sigma}$, the armature reaction reactance is proportional to the $\frac{q^2N_k^2k_{dp1}^2}{a^2}$, and is inversely proportional to the pole pitch τ, the equivalent length of airgap δ' and the airgap shear stress σ.

5.3 Slot leakage reactance

The slot leakage reactance can be calculated as:

$$X_{slot} = 2\pi f\times 8\mu_0\frac{pqN_k^2 l}{a^2}\lambda_s = 16\pi\mu_0\frac{n}{60}\frac{p^2qN_k^2 l}{a^2}\lambda_s$$

$$= 16\pi\mu_0\frac{n}{60}\frac{\pi^2D_i^2qN_k^2 l}{4\tau^2a^2}\lambda_s$$

Considering $D^2 l \approx \frac{60P_N}{\sigma\pi^2 n}$, then

$$X_{slot} = 4\pi\mu_0\frac{qN_k^2}{a^2}\frac{P_N}{\tau^2\sigma}\lambda_s$$

where $\lambda_s = \frac{3y+1}{4}\frac{h_0}{b_s} + \frac{9y+7}{16}\frac{h_w}{3b_s}$ is the slot leakage permeance coefficient, the slot open can be set as half of the tooth pitch, then $b_s = \frac{\tau}{2mq}$, therefore the height of slot is $h_w = \frac{2I_N}{aJb_s} = \frac{4mqI_N}{aJ\tau}$.

After that,

$$X_{slot} = \frac{32}{3}m^2\pi\mu_0\frac{q^3N_k^2}{a^3}\frac{P_N I_N}{\tau^4\sigma J}\frac{9y+7}{16}$$

So, $X_{slot} \propto \frac{q^3N_k^2}{a^3}\frac{1}{\tau^4\sigma J}\frac{9y+7}{16}$, the slot leakage reactance is proportional to the $\frac{q^3N_k^2}{a^3}$, and is inversely proportional to the fourth power of pole pitch τ^4, the current density J and the airgap shear stress σ. Also the pitch of coils would influence the slot leakage reactance. The slot leakage reactance increases dramatically with the increasing of pole pitch, because the decreasing of pole pitch makes the stator slot thinner and deeper, which also would make the slot leakage permeance coefficient increase rapidly.

5.4 End winding leakage reactance

It is difficult to calculate accurately with simple formulas because the conformation of the end windings is complex and difficult to characterize mathematically in simple terms. There are many ways to calculate but everyone has different result. For the electrical excited high speed generator and small motor, the end winding reactance is only a small fraction of the total reactance. But for the large diameter wind generator, the end winding reactance is an important component. The end winding leakage reactance can be calculated as:

$$X_{endt} = 2\pi f\times 8\mu_0\frac{pqN_k^2 l}{a^2}\lambda_e$$

where $\lambda_e = 0.57\frac{q\tau}{l}\frac{3y-1}{2}$ is the end winding leakage permeance coefficient.

$$X_{endt} = 2\pi\times 0.57\times 8\mu_0\frac{n}{60}\frac{p^2q^2N_k^2 l}{a^2}\frac{\tau}{l}\frac{3y-1}{2}$$

$$= 4\times 0.57\pi\mu_0\frac{q^2N_k^2}{a^2}\frac{P_N}{\sigma\tau l}\frac{3y-1}{2}$$

So, $X_{endt} \propto \frac{q^2N_k^2}{a^2}\frac{1}{\sigma\tau l}\frac{3y-1}{2}$, the end winding leakage reactance is proportional to the $\frac{q^2N_k^2}{a^2}$, and is inversely proportional to the pole pitch τ, the core length l and the airgap shear stress σ. Also the pitch of coils would influence the end winding leakage reactance.

5.5 Differential leakage reactance

The differential leakage reactance is only small fraction of the total leakage reactance, especially when the winding is short pitch and distributed. The differential leakage reactance can be calculated as:

$$X_{diff} = 4f\frac{\mu_0 D_i l}{p^2\delta'}(N_p k_{dp1})^2 \sum_{\substack{\nu=1,5,7,\cdots \\ \nu\neq 2k,3k \\ k=1,2,\cdots}} (\frac{k_{dp\nu}}{\nu k_{dp1}})^2$$

$$= \frac{8\mu_0}{\pi}\frac{q^2 N_k^2 k_{dp1}^2}{a^2}\frac{P_N}{\tau\delta'\sigma} \sum_{\substack{\nu=1,5,7,\cdots \\ \nu\neq 2k,3k \\ k=1,2,\cdots}} (\frac{k_{dp\nu}}{\nu k_{dp1}})^2$$

So, $X_{diff} \propto \frac{q^2 N_k^2 k_{dp1}^2}{a^2}\frac{1}{\tau\delta'\sigma}\sum_{\nu}(\frac{k_{dp\nu}}{\nu k_{dp1}})^2$, the armature reaction reactance is proportional to the $\frac{q^2 N_k^2 k_{dp1}^2}{a^2}$, and is inversely proportional to the pole pitch τ , the effective length of airgap δ' and the airgap shear stress σ. Also the pitch of coils would influence the differential leakage reactance.

From these equations and the analysis of the EMF and different components of synchronous reactance, some conclusions can be made for the optimization:

5 The EMF is proportional to $\frac{qN_k k_{dp1}}{a}$, while the armature reaction reactance is squarely proportional to $\frac{qN_k k_{dp1}}{a}$, which means the increase of armature reaction reactance would faster than that of EMF.

6 The airgap length is decided by mechanical consideration, it can not be shorten anymore. As well, the decreasing of the airgap length makes the armature reaction reactance increase linearly.

7 For the effective airgap length $k_\delta \delta$, $B_{1av} \propto \frac{h_M}{h_M + k_\delta \delta} B_r$. Usually the height of permanent magnet is 5 times the effective airgap length, the airgap flux density is 83% of the residence flux density of permanent magnet. It is not very useful to increase the height of permanent magnet. For example, when the height of permanent magnet is increased from 25mm to 35mm, i.e. 40%, the flux density only increases 4%.

8 Decreasing the airgap shear stress, the volume of generator becomes larger linearly.

9 The slot leakage reactance increases rapidly with the decrease of the pole pitch, so if the slot leakage reactance is higher than other components, then the pole pitch can be increased to decrease the slot leakage reactance.

10 The end winding leakage reactance is inversely proportional to the core length, so if the end winding leakage reactance is the highest part among the components, then the core length can be increased and the diameter can be decreased to decrease the end winding leakage reactance.

11 In order to decrease the synchronous reactance, the first step is to decrease the leakage reactance components. If it does satisfy the requirement, then the airgap length can be increased to decrease the armature reaction reactance. But inevitably, The increase the effective airgap length would cause to increase the volume of permanent magnet and the cost.

6. Design result of surface mounted permanent magnet wind generator

Using the software SPEED and the above analysis, many designs with different core length, different pole pair number, and different kinds of stator windings, have been calculated. The final design, that the power factor can reach 0.98 while the output power is 8MW and the weight is smallest among the designed generators, is chosen and shown in Table 4. From the parameters in table, it can be seen that the total leakage reactance is more than 50% of the synchronous reactance, which also indicates the importance of the optimization of leakage reactance components.

The airgap shear stress of final design is achieved as 55kPa, which is difficult to improve unless the current density is increased further.

Table 4 Final design results

Core Length	3500	mm
Rotor Diameter	4646	mm
Stator Outer Diameter	5012	mm
Rotor Inner Diameter	4911	mm
Pole Pair Number	45	
Airgap Length	6.5	mm
Magnet Height	32.5	mm
Pole Arc of permanent magnet	150°	
Turn Number per Coil	2	
Slot per pole per phase	1	
Slot type	Parallel square	
Slot Number	270	
Stator Winding Branch	1	
Slot Width	27.1	mm
Slot Depth	126.2	mm
Shape of Conductor	20×22	mm
Winding	Double layer	
Slot filled factor	0.519	
Total Phase Inductance	12.364	mH
Airgap component	4.753	mH
Slot leakage component	4.875	mH
End winding leakage component	2.735	mH
Differential leakage component	0.473	mH
X_d	0.951	Ω
X_q	0.943	Ω
E_q	2119	V

Bst	1.354	T
Bsy	1.963	T
Bry	1.074	T
Cu Weight	15432	kg
Fe Weight	65419	kg
Magnet Weight	10167	kg
Total Weight	91018	kg
Airgap Shear Stress	55	kPa

7. Conclusion

An 8MW directly driven surface mounted permanent magnet synchronous wind generator is designed in this paper which is aimed to decide whether or not the directly driven permanent magnet wind generator is suitable for the new wind turbine system. In order to optimize the performance, volume and weight, the EMF, armature reaction reactance, and different parts of leakage reactance are analyzed, based on which the optimization method and some hints were given. At last the optimized design results of 8MW generator are obtained.

Acknowledgements

This project was financially supported by the Baden-Württemberg government, Germany. The authors would like to acknowledge the financial support of Baden-Württemberg government, the technical support of the Institute of Power Electronics and Electrical Drives (ILEA) of Stuttgart University, and the arrangement and organization of the International Center of Stuttgart University, in Germany. Also the authors would like to thank Prof. Dr.-Ing. Martin Kühn of the chair for wind energy at Stuttgart University for his kind help.

References

[1] M.R. Dubois, Optimized permanent magnet generator topologies for direct-drive wind turbines, *Ph.D. dissertation*, Department Electrical Engineering, Delft University of Technology, 2004.

[2] Chan, T. T.; Lai , L. L., An Axial-Flux Permanent -Magnet Synchronous Generator for a Direct - Coupled Wind - Turbine System, *IEEE Transactions on Energy Conversion*, 22(1), 2007, 86 – 94.

[3] Dong Zhang; Shuangxia Niu; Chau, K.T.; Jiang, J.Z.; Yu Gong, Design and Analysis of a Double-Stator Cup-Rotor Directly Driven Permanent Magnet Wind Power Generator, *Proc 5th IEEE International Power Electronics and Motion Control Conference*, *IPEMC '06*, 2006, 1 – 5.

[4] Ki-Chan Kim; Seung-Bin Lim; Ki-Bong Jang, etc, Analysis on the direct-driven high power permanent magnet generator for wind turbine, *Proc of the Eighth International Conference on Electrical Machines and Systems, ICEMS 2005*, 243 – 247.

[5] Wang Fengxiang; Bai Jianlong; Hou Qingming; Pan Jian, Design features of low speed permanent magnet generator direct driven by wind turbine, *Proc of the Eighth International Conference on Electrical Machines and Systems, ICEMS 2005*, 1017 - 1020.

[6] Yicheng Chen, Pragasen Pillay, Azeem Khan, PM Wind Generator Comparison of Different Topologies. *Proc 39th IEEE IAS Annual Meeting*, 2004, 1405- 1412.

[7] Yicheng Chen, Pragasen Pillay, and Azeem Khan, PM Wind Generator Topologies, *IEEE Transactions on Industry Applications*, 41(6), 2005, 1619-1626

[8] Polinder, H.; van der Pijl, F.F.A.; de Vilder, G.-J.; Tavner, P.J.; Comparison of Direct-Drive and Geared Generator Concepts for Wind Turbines, *IEEE Transactions on Energy Conversion*, 21(3), 2006, 725 – 733.

[9] M.R. Dubois, H. Polinder and J.A.Ferreira, Comparison of generator topologies for direct-drive wind turbines, *Proc. International Conf. on Electrical Machine(ICEM) 92*, Manchester UK, 1992, 761-765.

[10] Grauers A., Design of Direct-driven Permanent-Magnet Generators for Wind Turbines, *PhD Thesis*, Chalmers University, Goteborg, Sweden, 1996

[11] E. Spooner and A.C. Williamson, Direct coupled, permanent magnet generators for wind turbine applications, *IEE Proceedings, Electric Power Applications*, 143(1) ,1996, 1-8.

[12] E.Spooner, A.C.Williamson and G.Catto, Modular design of permanent-magnet generators for wind turbines, *IEE Proceedings, Electric Power Applications*,. 143(5) ,1996, 388-395.

[13] http://www.multibrid.com/download/ M5000_ technical _data.pdf

[14] Lewis, C., The Advanced Induction Motor, *Proc. IEEE Power Engineering Society Summer Meeting*, 2002, 250-253.