Generator systems for wind turbines

H. Polinder
Electrical Power Processing
Delft University of Technology
The Netherlands
H.Polinder@ITS.TUDelft.NL

M.R. Dubois
EOCycle Technologies
Canada
MDubois@eocycle.com

J.G. Slootweg
Electrical Power Systems
Delft University of Technology
The Netherlands
J.G.Slootweg@ITS.TUDelft.NL

Abstract

This paper gives an overview of generator systems for wind turbines. First, the basic requirements for the drive system are related to the working principles of wind turbines. Next, the paper describes the three classical generator systems with their strengths and weaknesses: constant speed, variable speed with doubly-fed induction generator and variable speed with direct-drive generator. Besides, alternative generator systems and trends are discussed. There is a clear trend towards variable speed systems. Converters and permanent magnets are increasingly used because of their decreasing prices.

1 INTRODUCTION

The main factor which has stimulated the use of renewable energy is environmental protection. The cost disadvantage of renewable energy has resulted in numerous efforts to reduce its cost. For wind turbines, this has resulted in a continuously increasing rated power, as appears from figure 1 [1].

The goal of this paper is to give an overview over different generator systems for wind turbines. First, the basic requirements for the drive system are discussed from some basic wind turbine relations. Next, the paper describes the three classical generator systems with their strengths and weaknesses. Subsequently, alternative generator systems and trends are discussed.

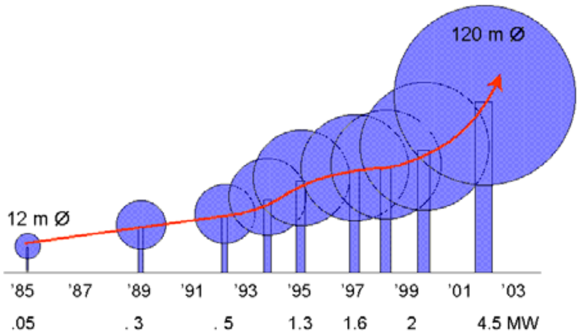

Figure 1: Development of power and size of wind turbines at market introduction [1].

2 BASIC RELATIONS

2.1 Wind turbine dimensions

The power that can be captured from the wind is given by [2]

$$P = \frac{1}{2}\rho_{air} C_p(\lambda,\theta)\pi r^2 v_w^3 \qquad (1)$$

where ρ_{air} is the air mass density [kg/m^3], $C_p(\lambda,\theta)$ is the power coefficient, depending on the tip speed ratio λ, which equals the ratio of tip speed v_t [m/s] over wind speed v_w [m/s] and the blade pitch angle θ [deg], and πr^2 is the rotor area (with r the rotor radius [m]).

An approximation of the dependence of the performance coefficient C_p on the tip speed ratio λ and the blade pitch angle θ is depicted in figure 2 [3]. This figure shows that for maximum energy capture from the wind, the rotor speed should be proportional to the wind speed.

There is a maximum rotor speed, mainly determined by the noise production of the blade tip. For on shore turbines, the tip speed is for this reason limited to roughly 70 m/s at rated wind speed. Therefore, if the tip speed is kept constant for different rotor surface areas, the rotational speed of the rotor is inversely proportional to the square root of the power:

$$N_{rated} = \frac{60}{2\pi}\frac{v_{trated}}{r} \propto \frac{1}{\sqrt{P_{rated}}}$$

where v_{trated} is the rated blade tip speed.

For offshore turbines, the noise does not play an important role, and higher speeds are used.

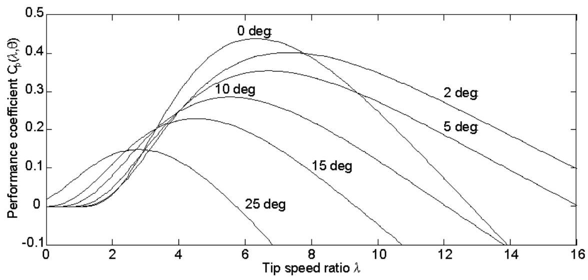

Figure 2: Performance coefficient C_p as a function of tip speed ratio λ and pitch angle θ [3].

The relation between wind speed and generated power is given by the power curve, as depicted in figure 3. In the power curve, four operating regions can be distinguished:

1. No power generation due to the low energy content of the wind.
2. Less than rated power generation. In this region, optimal aerodynamic efficiency and energy capture is aimed at.
3. Generation of rated power, because the energy content of the wind is enough. In this region, the aerodynamic efficiency must be reduced, because otherwise the generator system would become overloaded.
4. No power generation, because wind speeds are so high that the turbine could be damaged.

There are two main methods for limiting the aerodynamic efficiency in high wind speeds. With the first, the rotor blades are designed in such a way that their efficiency decreases automatically with increasing wind speeds. This is called stall power limitation. No active control systems are used to achieve this. With the second, the blades are gradually turned out of the wind using active controllers and hydraulic or electric actuators. This is called pitch control. For technical reasons, stall is mainly used with constant speed turbines and pitch with variable speed wind turbines. In figure 3, typical wind turbine power curves are depicted [4].

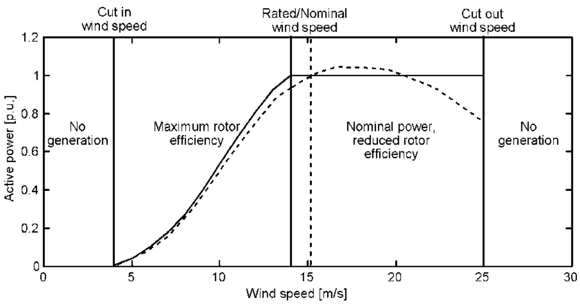

Figure 3: Typical power curve of a constant speed stall (dotted) and a variable speed pitch (solid) controlled wind turbine [4]

2.2 Generator dimensions

The force density (the force per square metre of air gap surface area) in electrical machines is a quantity that is rather constant over a wide range of machine powers. For the conventional generators used in wind turbines, the air gap force density is in the order of

$$F_d = 25 - 50 \text{ kN/m}^2$$

This force density is rather constant because it is the product of air gap flux density, which is limited because of magnetic saturation, and current loading, which is limited because of dissipation. By using forced liquid cooling, this force density can be increased, but at the cost of reduced efficiency.

Based on this force density, a very fast and rather good estimate of the generator dimensions can be made. The torque produced by a machine is given by

$$P = \omega T = \omega r_s F = 2\omega\pi r_s^2 l_s F_d$$

where ω is the mechanical angular frequency, r_s is the stator bore radius, and l_s is the stator stack length. From this, the rotor volume of a generator can be estimated as

$$V_r = \pi r_s^2 l_s = \frac{P}{2\omega F_d}$$

3 GENERATOR SYSTEMS

3.1 Currently used generator systems

Table 1 lists a number of wind turbine manufacturers with their products. The three most commonly used generator systems applied in wind turbines are depicted in figure 4 and discussed below.

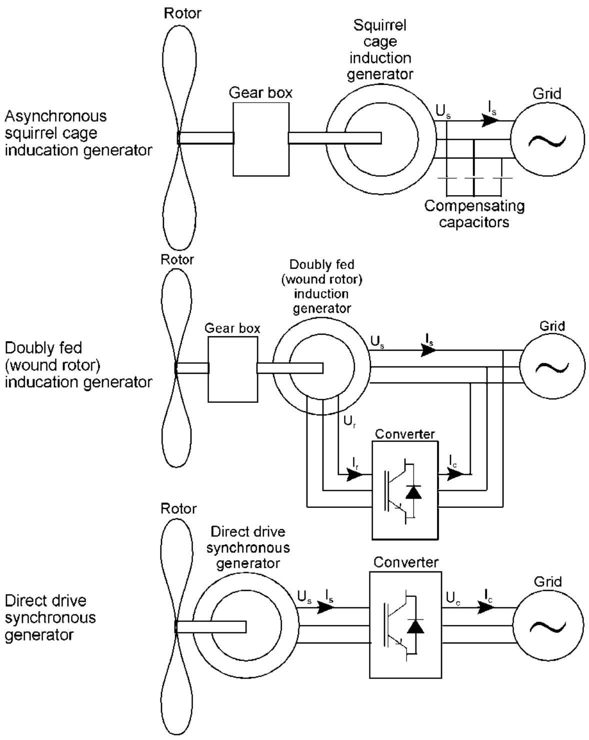

Figure 4: Three commonly used generator systems.

3.1.1 Constant speed wind turbine with squirrel cage induction generator

Between the rotor and the generator, there is a gearbox so that a standard (mostly 1500 rpm) squirrel cage induction generator can be used. The generator is directly connected to the 50 Hz or 60 Hz utility grid. Mostly, the power is limited using the stall principle: if the wind speed increases above the rated wind speed, the power coefficient inherently reduces, so that the power produced by the turbine stays near the rated power. There are a few variants:

1 pole changing generators with two stator windings with different numbers of pole pairs, and two constant speeds in order to increase energy yield and reduce noise production, and

2 generators with electronically variable rotor resistance in order to reduce mechanical loads by making speed variations possible: the semi variable speed wind turbine.

Table 1. Wind turbine manufacturers, currently used concepts and power ranges [4].

Manufacturer	Concept	Power range
Bonus (DK)	CT/CS CT/AS	600 kW; 1 – 2,3 MW
Dewind (UK/D)	VTDI	600 kW – 2 MW
Enercon (D)	VTDD	300 kW – 4,5 MW
GE Wind Energy (US/D)	CT/CS VTDI	600 kW; 900 kW – 3,6 MW
Lagerwey (NL)	VT/AGP VTDD	250 kW; 750 kW – 2 MW
Jeumont (F)	VTDD	750 kW – 1,5 MW
MADE (ES)	CT/CS VTSGP	660 kW – 1,3 MW 2 MW
NEG Micon (DK)	CT/CS CT/AS VTDI	600 kW – 1,5 MW 1,5 – 2 MW 2,75 MW
Nordex (D)	CT/CS VTDI	600 kW – 1,3 MW 1,5 – 2,5 MW
Repower Systems (D)	CT/CS CT/AGP VTDI	600 – 750 kW 1050 kW 1,5 – 2 MW
Vestas (DK)	SVT/OSP VTDI	660 kW – 2,75 MW 850 kW – 3 MW

CT/CS fixed speed, classic stall (fixed blade angle)
CT/AS fixed speed, active stall (negative variable blade angle, 3-5 degrees)
VTDI variable speed (+ pitch), doubly-fed induction generator
VTDD variable speed, direct drive synchronous generator combined with pitch (Enercon + Lagerwey + 1.5 MW Jeumont) or combined with classic stall (Jeumont J48 (750 kW))
VTSGP variable speed/pitch combined with (brushless) synchronous generator
VT/AGP variable speed /pitch combined with asynchronous generator (100% current via converter)
CT/AGP nowadays unusual combination of fixed speed /pitch with directly connected asynchronous generator
SVT/OSP semi-variable speed/pitch combined with OptiSlip (maximum +10% variation in nominal speed)

3.1.2 Variable speed wind turbine with doubly-fed (wound-rotor) induction generator

Between the rotor and the generator, there is a gearbox so that a standard (mostly 1500 rpm) doubly-fed induction generator can be used. The stator is directly connected to the utility grid. The rotor is connected to a converter. A speed variation from roughly 60% to 110 % of the rated speed is sufficient for a good energy yield, that is achieved by using the variable speed capability to keep the tip speed ratio λ at the value resulting in optimal energy capture. A converter rating of roughly 35 % of the rated turbine power is sufficient, particularly when star-delta switching at the rotor winding is applied. At wind speeds above the rated wind speed, the power is mostly reduced by pitching the blades.

3.1.3 Variable speed wind turbines with direct-drive synchronous generator

In this system, no gearbox is necessary, because the generator rotates at very low speed. Standard generators can therefore not be used and generators have to be developed specifically for this application. The total turbine power goes through a converter that converts the varying generator frequency to the constant grid frequency. At wind speeds above the rated wind speed, the power is again mostly reduced by pitching the blades.

3.2 Comparison of the three systems

Table 2 gives an overview of the characteristics of the three different systems. The criteria for comparison are discussed below [5].

3.2.1 Cost, size and weight

Squirrel cage induction generators are 25% cheaper than doubly-fed induction generators.

The converter for a doubly-fed induction machine is smaller and cheaper than for a direct-drive generator.

Direct-drive generators are much more expensive because they are large and heavy and have to be specially developed. However, direct drive turbines do not need a heavy gearbox.

3.2.2 Energy yield

In order to capture the maximum energy from the wind, the rotor speed has to be proportional to the wind speed in region 2 of figure 3. Therefore, the energy yield of variable speed wind turbines is larger than of constant speed wind turbines.

The efficiency of the systems is probably similar: geared systems have considerable losses in the gearbox, while direct-drive systems have more losses in the generator and the converter.

Table 2. Comparison of the three wind turbine concepts, +: strength, -: weakness.

	CS	VTDI	VTDD
Cost, size and weight	+	+/-	-
Energy yield	-	+	+
Reliability and Maintenance			
Brushes	+	-	- (PM:+)
Gearbox	-	-	+
Mechanical loads	-	+	+
Complexity	+	-	-
Audible noise	-	+	+
Power quality			
'Flicker'	-	+	+
V/f control possible	-	+	+
Harmonics	+	-	-
Grid faults			
Contribution to fault currents	+	-	+/-
Contribute to restoring voltage	+/-	-	+

3.2.3 Reliability and maintenance

Brushed synchronous generators and doubly-fed induction generators have brushes, which need regular inspection and replacement. Permanent magnet (PM) generators don't have this problem.

Gearboxes are widely used, well-known components with lots of applications. However, in wind turbines, gearboxes show a past reliability record that is rather negative [6].

The heavier mechanical loads of constant speed wind turbines may lead to a decrease in reliability and an increase in maintenance.

3.2.4 Audible noise

In a well-designed wind turbine, the blades are the main sources of audible noise. In variable speed wind turbines, the rotor speed is low at low wind speeds, and so is the audible noise.

3.2.5 Power quality

Figure 5 depicts measurements of wind speed sequences and the resulting rotor speeds, pitch angles and output powers for the three most used generator systems at wind speeds around the rated wind speed. It appears that the power output of variable speed wind turbines is much smoother (less 'flicker') than constant speed wind turbines because rapid changes in the power drawn from the wind are buffered in rotor inertia. The fast power fluctuations in constant speed wind turbines are caused by variations in wind speed, but also by the tower shadow.

If the converter rating is large enough, variable speed wind turbines also can be used for voltage and frequency (V/f) control in the grid (within the limits posed by the actual wind speed) [7], which isn't possible with constant speed wind turbines.

Power electronic converters produce harmonics that may need to be filtered away.

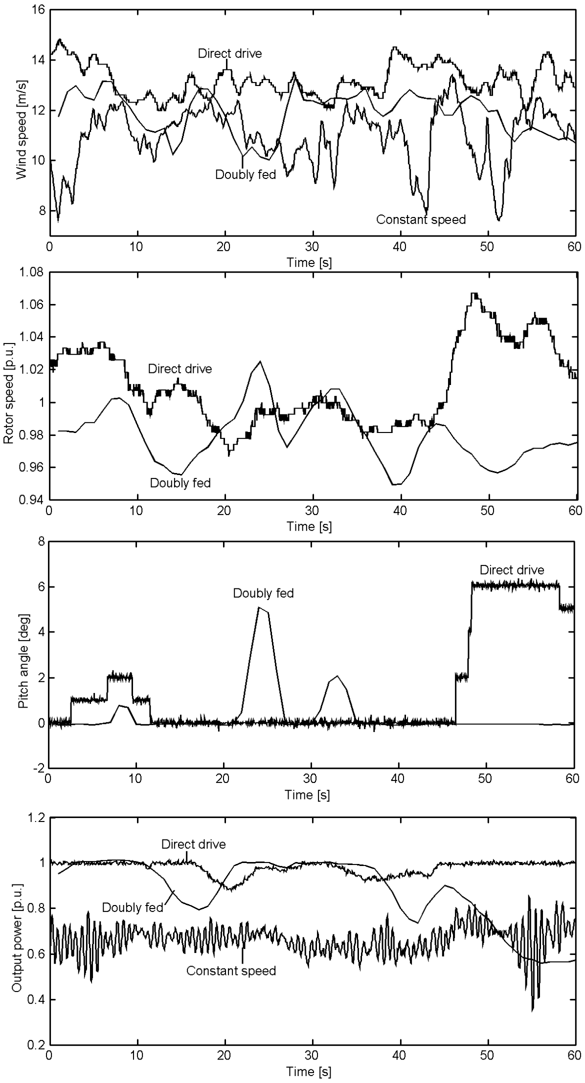

Figure 5: Measured wind speeds and resulting rotor speeds, pitch angles and output powers for the three different generator systems.

3.2.6 Grid faults

The three concepts behave differently in case of a grid fault causing a voltage dip.

In case of a fault, constant speed wind turbines can deliver the large fault currents, necessary for activating the protection system. However, when the voltage comes back, they consume a lot of reactive power and thus impede the voltage restoration after the dip.

In case of a fault, the rotor currents in a doubly-fed induction generator increase very rapidly and the turbine is disconnected from the grid within milliseconds in order to protect the converter. In grids with a lot of wind turbines, disconnecting all wind turbines leads to problems with the power balance (generated power must be equal to consumed power), which is essential for a correct functioning of a power system. This also

implies that these wind turbines do not help in restoring the voltage after a voltage dip; when the conventional power stations have restored the voltage, the wind turbines can be reconnected.
In case of a fault, turbines where all power goes through a converter could stay connected [8]. The converter can theoretically limit the current to rated values during dips, delivering power at reduced voltage levels. Therefore, these turbines may help the conventional power stations in rebuilding the voltage after grid failures.

4 ALTERNATIVES AND TRENDS

4.1 Alternative generator systems

A few manufacturers have produced variable-speed wind turbines with squirrel cage induction generators with a converter carrying the full power. Compared to the doubly-fed induction generator this system has the following advantages

- the generator is cheaper,
- the generator has no brushes,
- the system is often used as industrial drive,
- it is not necessary to disconnect the wind turbine in case of grid faults when advanced algorithms are used to control the converter,

and the following disadvantages

- larger, more expensive converter (100% of rated power instead of 35%)
- higher converter losses because all power is carried by the converter.

From the fact that this solution is rather seldom, it can be concluded that its disadvantages are more important than the advantages.
Recently, the Spanish manufacturer Made developed a geared wind turbine with a brushless synchronous generator and a full converter (VT/SGP in table 1). Compared to the doubly-fed induction generator, this generator system has the following advantages

- the generator has a slightly better efficiency,
- the generator has no brushes,
- it is not necessary to disconnect the wind turbine in case of grid faults when advanced algorithms are used to control the converter,

and the following disadvantages

- larger, more expensive converter (100% of rated power instead of 35%), and
- higher converter losses because all power has to go through the converter.

It is possible that the steady decrease in cost of power electronics (roughly a factor 10 over the past 10 years) will make this an attractive system in the near future, mainly because of the better characteristics in case of grid failures.

4.2 Trends in geared generator systems

The first trend to be mentioned is the fact that in recent years, many wind turbine manufacturers changed from constant speed to variable speed systems for the higher power levels for reasons mentioned in section 3.2.
At the moment, a fundamental problem in variable speed wind turbines with doubly-fed induction generator is that they cannot stay connected to the grid in case of grid failures, although grid owners increasingly require this. As long as this problem is not solved, the brushless synchronous generator system is a serious competitor. However, if it would be solved, we do not see the brushless synchronous generator as a serious competitor.

4.3 Trends in direct-drive generator systems

Most of the current direct-drive generators are electrically-excited synchronous generators (Enercon, Lagerwey). Some manufacturers work on permanent-magnet synchronous generators (Lagerwey, Jeumont). At the moment Enercon and Lagerwey started developing direct-drive generators in the early nineties, permanent magnets were too expensive. Although magnet prices dropped by roughly a factor 10 over the past 10 years, manufacturers tend to stick to well-known and proven solutions.
The advantages of permanent-magnet excitation when compared to electrical excitation are lower losses (no excitation losses) and lower weight (nearly a factor 2 in active material). A disadvantage is that the excitation can not be controlled. According to [9,10], permanent-magnet generators are nowadays more attractive than electrically-excited synchronous generators.
Direct-drive generators usually are not standard machines. Therefore, it is worthwhile to study the use of alternative generator topologies which offer the possibilities of further weight and cost reduction.
Axial flux generators generally are smaller, but also heavier and more expensive than radial flux machines [11]. This is caused by the fact that in axial flux machines the force density introduced in (3) is not be optimal for all radii, and by the fact that the radius where the force works is not always maximum.
The use of transverse flux generators (see figure 6) is investigated [12] because according to the literature [13,14], they have very high force densities. However, because of the large air gap in large direct-drive generators, it is questionable whether these generators have higher force densities in this application. A strength of transverse flux generators is the simple winding,

which offers possibilities for high voltages. A weakness is the complex construction, which may result in mechanical problems and audible noise. In the TFPM machine with toothed rotor proposed in [12], some rotor construction problems are solved.

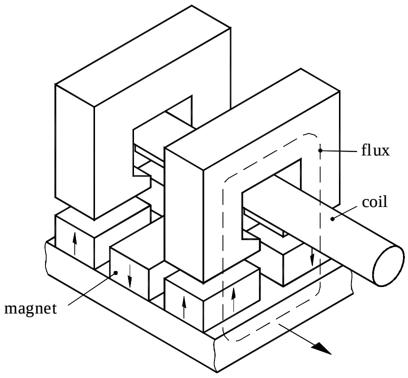

Figure 6: Transverse flux permanent magnet generator.

4.4 Trends in voltage levels

A few years ago, ABB came with the wind former, a medium voltage generator. Enercon generators mostly have the low voltage level of 400 V. For larger wind turbines, most wind turbine manufacturers use voltage levels of 700 V. Lagerwey's Zephyros works at 3 kV.

In principle, the voltage level does not matter for the generator electromagnetic design. By doubling the number of turns in a slot and halving their cross-section, the voltage level can be doubled while the amount of copper in the slot remains the same. However, at low voltage levels, huge cables are necessary between the generator terminals and the transformers. At voltage levels above a few kV, the conductor insulation takes more space. Therefore, the amount of copper in the slots is reduced and bigger generators are necessary to convert the same power. Besides, power electronic converters for voltage levels in the order of several kV have become available. Therefore, an increase of the voltage level to several kV can be expected, but not to values far above 4 kV.

5 CONCLUSIONS

There is a trend toward variable speed generator systems for wind turbines. In geared technology, the doubly-fed induction generator needs a solution to prevent disconnection from the grid due to grid faults. If such a solution is not found, brushless alternatives where all power goes through the converter may become serious competitors. In direct-drive technology, the use of permanent magnets can be expected to increase. The use of voltage levels above a several kV is not expected.

References

[1] G.A.M. van Kuik, 'Are wind turbines growing too fast?', *Proc. European Wind Energy Conference and Exhibition*, Copenhagen, 2001, pp. 69-72.

[2] S. Heier, *Grid integration of wind energy conversion systems*, Chicester: Wiley, 1998.

[3] J.G. Slootweg, H. Polinder, W.L. Kling, 'Dynamic Modelling of a Wind Turbine with Direct Drive Synchronous Generator and Back to back Voltage Source Converter and its Controls', *Proc. European Wind Energy Conference and Exhibition*, Copenhagen, 2001, pp. 1014-1017.

[4] J.G. Slootweg, E. de Vries, 'Inside wind turbines-Fixed vs. variable speed', *Renewable Energy World*, 2003, pp. 30-40.

[5] M.R. Dubois, H. Polinder, J.A. Ferreira, 'Generator topologies for direct-drive wind turbines, and adapted technology for turbines running in cold climate', *Proc. conference on wind energy in cold climates*, Matane, Canada, 2001.

[6] 'Another gearbox failure', *Wind power monthly,* December 2000.

[7] J.G. Slootweg, S.W.H. de Haan, H. Polinder, W.L. Kling, 'Voltage Control Methods with Grid Connected Wind Turbines: a tutorial review', *Wind Engineering*, 2001, pp. 353-365.

[8] G. Saccomando, J. Svensson, A. Sannino, 'Improving voltage disturbance rejection for variable-speed wind turbines', *IEEE Transactions on Energy Conversion*, 2002, pp. 422-428.

[9] S. Jöckel, 'Gearless wind energy converters with permanent magnet generators – and option for the future?', *Proc. European Union Wind Energy Conference*, 1996, pp. 414-417.

[10] A. Grauers, 'Design of direct-driven permanent-magnet generators for wind turbines', PhD-thesis, Göteburg, Sweden, 1996.

[11] M. R. Dubois, H. Polinder, and J. A. Ferreira, 'Comparison between Axial and Radial-Flux Permanent Magnet Generators for Direct-Drive Wind Turbines', *Proc. European Wind Energy Conference and Exhibition*, Copenhagen, July 2-6, 2001, pp. 1112-1115.

[12] M.R. Dubois, H. Polinder, J.A. Ferreira, 'Transverse-flux permanent magnet (TFPM) machine with toothed rotor', *Proc. IEE International Conference on Power Electronics, Machines and Drives*, Bath, 2002, pp. 309-314.

[13] H. Weh, H. May, 'Achievable force densities for permanent magnet machines in new configurations', *Proc. international conference on electrical machines*, 1986, pp 1107-1111.

[14] M.R. Dubois, H. Polinder, J.A. Ferreira, 'Comparison of generator topologies for direct-drive wind turbines', *Proc. Nordic Countries Power and Industrial Electronics Conference (NORPIE),* Aalborg*,* 2000, pp. 22-26.