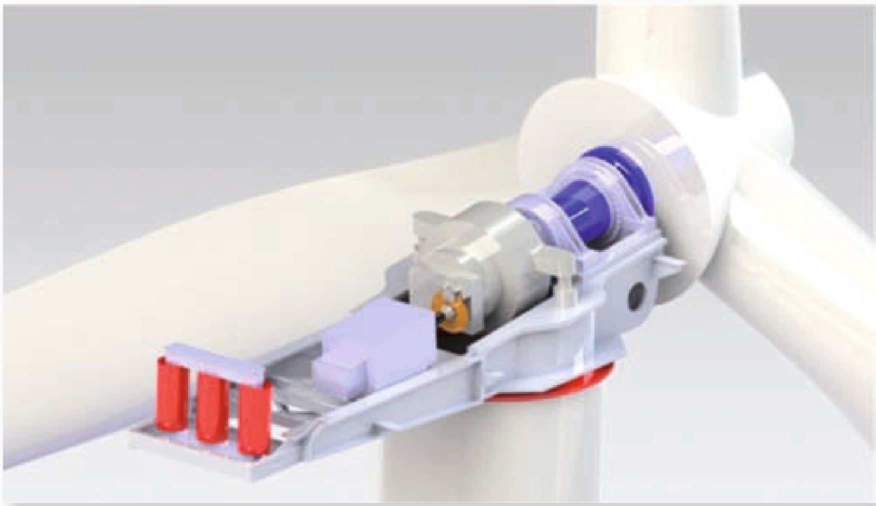
2nd CONFERENCE FOR WIND POWER DRIVES

CWD 2015



CWD Center for Wind Power Drives
RWTH AACHEN UNIVERSITY

2nd CONFERENCE FOR WIND POWER DRIVES

CWD 2015

Conference Proceedings

Aachen, 3rd - 4th of March 2015

Published by

Univ.-Prof. Dr.-Ing. Dirk Abel (Institut für Regelungstechnik)
Univ.-Prof. Dr.-Ing. Christian Brecher (Werkzeugmaschinenlabor der RWTH Aachen)
Univ.-Prof. Dr. ir. Rik W. De Doncker (Power Generation and Storage Systems)
Univ.-Prof. Dr.-Ing. Dr. h.c. Kay Hameyer (Institut für elektrische Maschinen)
Univ.-Prof. Dr.-Ing. Georg Jacobs (Chair for Wind Power Drives)
Univ.-Prof. Dr.-Ing. Antonello Monti (Automation of Complex Power Systems)
Univ.-Prof. Dr.-Ing. Wolfgang Schröder (Aerodynamisches Institut)

CWD Center for Wind Power Drives
RWTH AACHEN UNIVERSITY

Supported by

winergy

6 MW Windenergieanlage mit mehreren hochdrehenden Generatoren

6 MW Wind Turbine with Multiple High-speed Generators

Simon Serowy*[1], Cristian Andrei[2]

Friederike Barenhorst[1], Dr. Ralf Schelenz[1],
Prof. Dr. Georg Jacobs[1], Rüdiger Appunn[2],
Prof. Dr. Kay Hameyer[2]

[1]Institute for Machine Elements and Machine Design (IME), RWTH Aachen University
Schinkelstraße 10, 52062 Aachen, Deutschland

[2]Institute of Electrical Machines (IEM), RWTH Aachen University
Schinkelstraße 4, 52062 Aachen, Deutschland

Supported by:

Federal Ministry
for Economic Affairs
and Energy

on the basis of a decision
by the German Bundestag

Contents

1 Abstract

State-of-the-art wind turbine (WT) drive train concepts still display major drawbacks – despite their technological maturity and market domination –, especially regarding size, efficiency and availability. Therefore, alternative concepts have to achieve following objectives: increased efficiency and power density, reduced weight and size, reduced investment costs, increased economic efficiency in production and low downtimes.

In order to accomplish these goals, a 6 MW WT drive train with six high-speed (5000 min^{-1}) generators is presented in this paper. This drive train combines the advantages of WT concepts with multiple generators with the high-speed technology of electrical machines. High-speed electrical machines offer an increase of power density and cost reduction, which is not used in WTs so far.

The gearbox used for this concept needs a higher ratio compared to conventional configurations. This can lead to additional complexity and losses. However, these drawbacks can be compensated by an optimized operating strategy and the benefits of the high-speed machines. The targeted higher speed results in an increased power density, which leads to a considerable weight and size reduction of the generators. This, furthermore, reduces the amount of magnetic active material and thus decreases investment costs. The design with multiple equal generators enables the utilization of more identical parts. Concurrently, these parts are smaller and more lightweight due to the power split configuration. As a result increased economic efficiency in production and improvements in maintenance can be achieved. A certain redundancy of the system is given as well, since energy will still be produced, even in case of a malfunction of one generator.

2 Introduction

With the trend to further increase performance and the expansion of WTs in low wind areas, the rotor diameters are consistently becoming larger. Larger rotor diameters lead to lower rotor speeds and larger rotor torques. This results in larger gearboxes and generators. In general special generators are used in multi-megawatt WTs instead of compact, high-speed generators, which are offered by numerous manufacturers. The use of generators that operate at higher speeds is not yet taken into account in the wind energy industry. High-speed generators allow savings of space, weight and cost, because while operating at the same power lower torques have to be transmitted [KNO10]. The reduction of magnetically active material as a cost driver of WT generators leads to a significant cost reduction and greater independence from the price development of noble earth elements.

Main feature of the drive train concept proposed in this paper, in addition to the application of high-speed electrical machines, is the multi-generator configuration using six 1 MW generators.

Similar concepts with multiple generators and power split configuration are already present on the wind energy market (see Image 1:), but none of them take full advantage of the power density and size reduction that can be achieved by using such configurations. The Clipper Liberty WT for example uses four 650 kW generators that rotate at only 1133 min^{-1} [CLI08]. Thus the generators are bulkier than the ones of the concept proposed here, despite the PM technology used for the excitation and the higher power density that comes with it. Another example is the Multi Duored gearbox from Winergy, which has a transmission ratio of only 1:140 and cannot be used for high-speed generators like the ones proposed here [HAN12]. Although the number of identical parts of this gearbox is relatively high due to the eight times load sharing, this aspect is not fully exploited, since only two output shafts are used [WIN14]. Furthermore, the eight times power split and subsequent four times power summation, which results in the two outputs, makes this gearbox concept even more prone to mechanical failures.

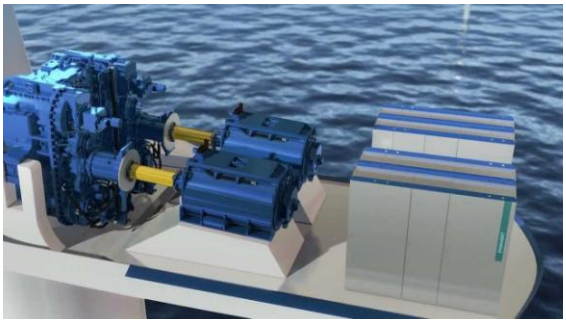


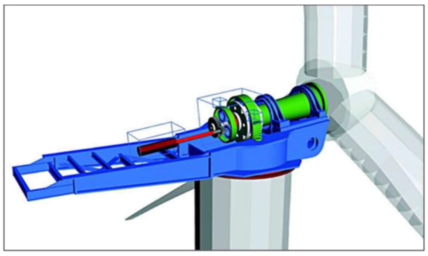
Image 1: WT drive trains with multiple generator outputs: Clipper Liberty (left) and Winergy Multi Duored (right).

3 Wind Turbine Generic Model

To determine the input loads for the design of the new drive train a generic system model of a conventional WT (see Image 2) [BER11] is used. This generic model with a rated power of 6 MW at the Point of Common Coupling is designed for an IEC class Ia wind site (strong winds). Based on the geometry of the rotor, the hub height and the wind conditions, the input loads for the design of the drive train are determined, such as rated speed, rated torque and rotor thrust. Due to a presumed overall efficiency of the WT of 90 %, a mechanical input power of 6.7 MW on rotor side is assumed for rated operation. These values are used as input for the concept development of the gearbox and the generator. Beside the implementation for strong winds, low wind conditions (IEC III wind class) are considered as well. For this purpose a low wind rotor with a diameter of 164 m is designed for the generic WT model. Based on the operational strategy of the generic WT with the operating conditions – start-up, partial load operation, full load operation and emergency stop –, a new strategy, especially for partial load operation, is adapted to consider the use of six generators at high speed.

IME 6.0

Type	Off-Shore	
Rated power	6	MW
Wind speed	3-25	m/s
Rated wind speed	11.9	m/s
Rotor diameter	126	m
Rotor speed	6.9-12.1	min^{-1}



Input parameters

Input power	6.7	MW
Rotor speed	12	min^{-1}
Torque	5.33	MNm
Thrust force at rated wind speed	780	kN

Image 2: IME 6.0 WT generic model and its input parameters

4 Gearbox Configurations

The development of gearbox concepts for the high-speed multi-generator drive train is basically similar to the structure of conventional WT gearboxes. It is built as a combination of planetary and spur gear stages, where said planetary stages are considered exclusively in the two-shaft mode in order to restrict the solution space. With the use of planetary gears a compact space with high power density can be obtained and usually ratios of 1:7 can be realized [GAS11]. To implement the power split to six generators, a spur gear is used. Since the intended rated speed of the generators for strong and low WT configurations is in a speed range of 5000 min^{-1}, the gearbox needs to have a transmission ratio higher than 1:400. To realize this ratio four gear stages are needed. Under these requirements and the requirement for space and durability, shafts, bearings and gears are sized based on the rated load. In Image 3 four transmission structures are shown, which were taken into account. They are composed of three planetary gear stages and one spur gear stage. The planetary gears are driven by the planet carrier and the output is realized through the sun shaft. The number of used planets in the first stage is either five or three. The differences between the shown concepts are characterized by the position of the spur gear stage and thus the position of the power split to the six output shafts.

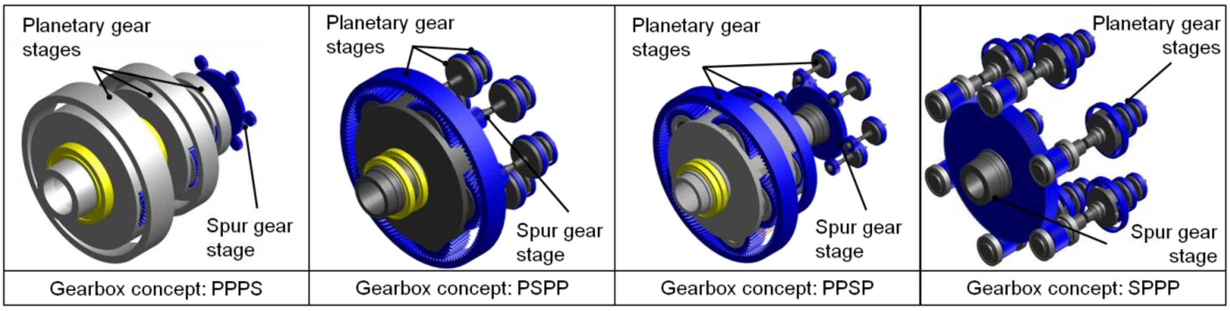


Image 3: Gearbox structures

The developed concepts are rated regarding space, weight, modularity (number of parts and identical components) and efficiency. Using planetary gear units in the first three stages leads to a compact gearbox design, with the power split in the last stage. In contrast to this structure, the first stage can be carried out with spur gears, so that the power is split to six 1 MW drive trains already in the first stage. This is a very modular gearbox structure, increases the number of identical parts and leads to a weight reduction of the individual components. The remaining concepts provide the power split in the second and third stage, respectively. In Table 1 the dimensions of the four designs are summarized. Compared to conventional gearbox structures the developed concepts are more complex, which is caused by the power split and the fourth gear stage. Nevertheless, the dimensions of the developed concepts are promising, since the alternative drive train design is of a comparable size to conventional drive train designs, due to weight and size reduction of the generators.

Gearbox concept	**Maximum width [m]**	**Maximum length [m]**	**Weight [t]** (Gears, shafts, bearings)	**Number of parts**		
				Gears	Bearings	Shafts
PPPS	3.4	3.4	47	24	46	24
PSPP	3.4	3.2	45	74	124	74
PPSP	3.4	3.4	49	49	96	49
SPPP	4.2	3	40	97	182	97

Table 1: Comparison of gearbox concepts

The evaluation of the gearbox concepts regarding their efficiency is done on a system level, including main bearing and generator (see chapter 6). Future challenges for the gearbox design, caused by the high speed, are the execution of the cooling and lubrication system, as well as the initiation of the prestressing forces for the bearings.

5 Generator Topology

Three electrical machine topologies are analyzed in this section: the squirrel cage induction machine (SCIM), the electrically excited synchronous machine (EESM) and the synchronous machine with permanent magnet (PM) excitation (PMSM).

Before starting with the analytical design, a series of parameters and modeling characteristics have to be assumed. These parameters are defined based on specifications in [MÜL08] and rely mostly on experience. At the same time, thermal limitations and saturation of the magnetic active material are taken into account. Starting from these parameters, the main geometric dimensions of the machines (e.g. the outer diameter or the laminations stack length) must be determined first and then used for the detailed winding layout. To be able to calculate the bore diameter, the ideal length of the magnetically active material and the pole pitch, a corresponding Esson coefficient must be chosen. With the aid of the pole pitch, the number of slots per pole and phase can be determined. Furthermore, the pole pitch influences the magnetic flux in the air gap, which also depends on the average magnetic field in the air gap. The number of turns can then be calculated, if it is assumed that the magnetic flux in the air gap corresponds to the main flux.

In the rotor, the slot geometry of the SCIM results from the calculation of the current in the bars and in the short-circuiting rings of the rotor cage. For the EESM the slot geometry is given by the excitation current. In the case of the PMSM the arrangement and the geometry of the PMs must be determined. For the basic calculations implemented here, only a rotor with surface mounted PMs can be considered.

After the calculation of the winding and machine dimensions, the copper and iron losses have to be determined. The copper losses result from the resistances and the currents of the windings in the stator and the rotor. In order to determine the iron losses in the electrical sheets of the machines, the approach described in [EGG12] is applied. Hereby the iron losses are determined based on the specific mass of the used steel m_{Fe}, the peak value of the magnetic field $\hat{B}$ and the frequency f in the sheets. The coefficients $a_1 - a_5$ are material dependent and determined by measurements:

$$P_{losses,Fe} = m_{Fe} \cdot \left[a_1 \cdot \hat{B}^2 \cdot f + a_2 \cdot \hat{B}^2 \cdot f^2 \cdot \left(1 + a_3 \cdot \hat{B}^{a_4}\right) + a_5 \cdot \hat{B}^{1,5} \cdot f^{1,5}\right] \qquad \textbf{Eq. 1}$$

Finally, the efficiencies and power densities of the three investigated machine topologies can be calculated based on their losses and geometric dimensions:

		SCIM		**EESM**		**PMSM**	
Outer diameter	D_{out}	0.42	m	0.52	m	0.47	m
Total length	l_{tot}	0.66	m	0.54	m	0.65	m
Volume	V	0.090	m^3	0.113	m^3	0.115	m^3
Power density	P_δ	11.15	MW/m^3	8.85	MW/m^3	8.70	MW/m^3
Efficiency	η	95.4	%	97.7	%	97.3	%

Table 2: Results of the analytical design

The SCIM has the highest power density and the EESM the highest efficiency, but the differences are relatively small in comparison to the PMSM. This aspect shows that the accuracy of an analytic investigation is insufficient. However, we know from experience that a significant increase of the efficiency of the PMSM can be expected if an arrangement with V-shaped buried magnets (V-PMSM) is used [FIN10], which is why a V-PMSM is considered as a generator for now (see Table 3 and Image 4).

General data			
Rated power	P_N	1	MW
Rated voltage	U_N	690	V
Rated speed	n_N	5000	min^{-1}
Active length	l_i	480	mm
Stator			
Outer radius	$r_{S,out}$	240	mm
Yoke height	h_j	34	mm
Tooth width	b_t	20.4	mm
Slot height	h_s	53.6	mm
Air gap	δ	2.4	mm
Rotor			
Outer radius	$r_{R,out}$	150	mm
Inner radius	$r_{R,in}$	70	mm
PM angle	α_{PM}	70	°
PM height	h_{PM}	10	mm
Pole coverage	α_i	0.7	

Table 3: V-PMSM design parameters

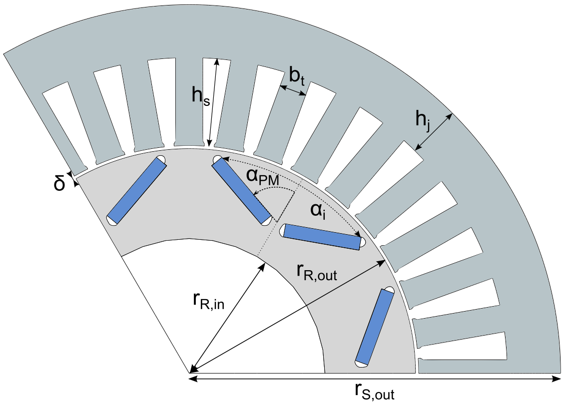


Image 4: Geometry model of the V-PMSM

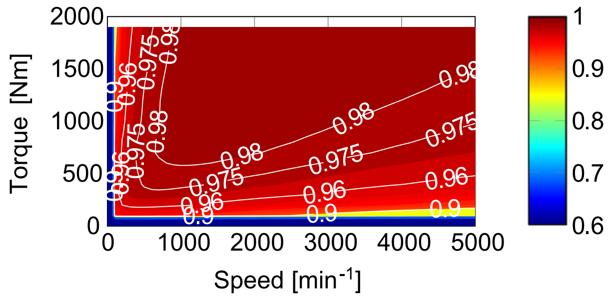


Image 5: Efficiency map of the V-PMSM

The six identical generators are implemented in the corresponding blocks of the system model in chapter 6 based on their efficiency maps. In order to determine this efficiency map as accurately as possible, an existing V-PMSM geometry is scaled to the required power of 1 MW and designed numerically with the help of finite element method (FEM) calculations. The maximum efficiency determined for the V-PMSM is 98.27 % (see Image 5). The geometric dimensions of the machine yield a total volume of magnetically active material of 0.087 m^3, as well as a power density of 11.5 MW/m^3. When comparing these results to those of the analytical design (see Table 2), the need for a more accurate numerical investigation becomes obvious once again. Therefore, the other two machine types (SCIM and EESM) will also be considered for FEM calculations in future works. Only then a reasonable choice between the three electrical machine topologies can be made.

6 Efficiency Evaluation of the Drive Train

For the presented gearbox and generator concepts, models are developed to determine the efficiency for the different drive train concepts. The entire drive train is considered consisting of a main bearing, a gearbox and six generators. The main bearing is constructed as a fixed-floating bearing, as it is used in four-point mounting concepts.

The various gearbox structures are described by the used bearings and their gears. To determine the efficiency as an evaluation parameter, the total power losses P_L in bearings, gears and seals are calculated. There are load-dependent losses (P_B or P_G) and load-independent losses (P_{B0} or P_{G0}) in the bearings and gears. The seal losses P_S are independent of load and are calculated according to [LIN10]. The total power losses of the entire drive train concepts amount to

$$P_L(\bar{v}_w) = \sum_i \left[P_{B_i} + P_{B0_i}\right] + \sum_i \left[P_{G_i} + P_{G0_i}\right] + \sum_i \left[P_{S_i}\right] + P_{L_{Generator}} \qquad \textbf{Eq. 2}$$

The bearing losses for the main bearing and for all bearings in the different gearbox concepts are calculated based on the calculation method from [SAE09]. They are dependent on the bearing geometry, the properties of the lubricant, the attacking bearing forces and the speed. In the gear teeth hydrodynamic losses and losses caused by friction occur. The friction in the gear contacts is divided into sliding and rolling friction. The calculation method for these load dependent gear losses is based on [AND80] and calculated for each gear meshing. The hydrodynamic losses consist of paddling and trapped losses. The paddling losses are caused by the immersion of the gears in the oil sump and the intermingling of the oil. The power which is necessary to displace the oil during the tooth contacts is referred to as trapped losses. The hydrodynamic losses could not be included in the calculation models so far. The generator losses ($P_{L,Generator}$) are considered in the system models based on the characteristic efficiency diagram of the V-PMSM configuration described in chapter 5. The efficiencies calculated with these models, are determined for the average wind speed and at an oil temperature of 65 °C. The operating strategy for this first efficiency analysis is similar to conventional strategies with a speed control during partial load and power control during full load operation. Hereby all six generators are active, even during partial load operation. The efficiency during full load operation is 91.42 % for the drive train concept with the gearbox structure SPPP and 91.50 % for the concept with the PPPS structure. The efficiency of the PPPS gearbox concept is better than that of the SPPP concept, mainly in the partial load range at lower rotor speeds the different amounts up to 2 %. This can be explained by the fact that in the SPPP concept more rotating parts and bearings are installed which produce higher total power dissipation. Due to the slightly different transmission ratios of the two gearboxes, generator speed and torque are slightly different for the two concepts. This leads to a small difference in the efficiency results of the generator (see Image 6). The other concepts are not considered here, but similar efficiency characteristics are expected due to the similar gearbox structures. At this point the efficiency simulation is executable and differences between various drive train configurations can be determined.

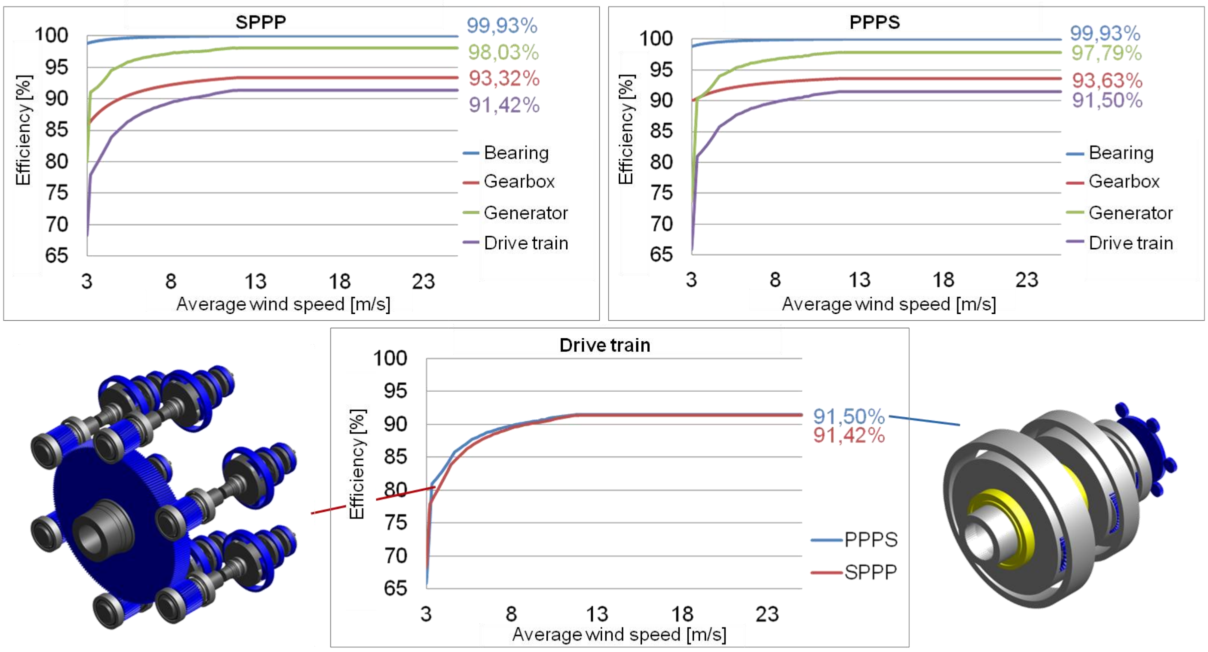
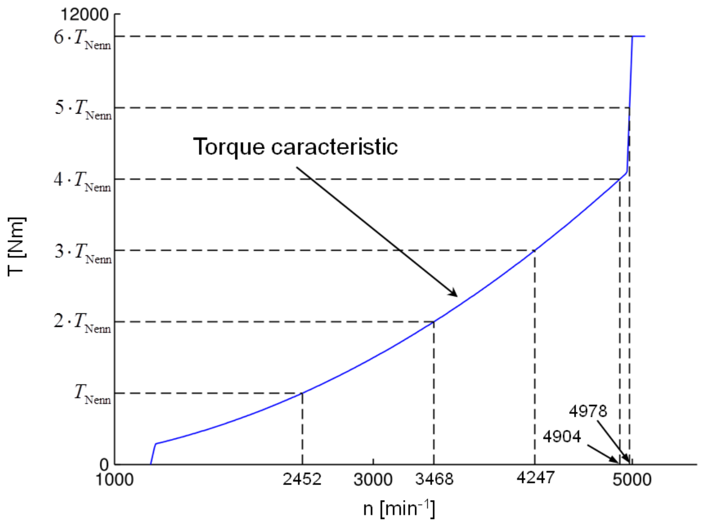


Image 6: Results of the efficiency simulation

7 Operating Strategy

As seen in the results of the efficiency simulation (see Image 6), the power losses are reduced while operating under full load. In the case of a drive train concept with multiple generators the possibility is seen to switch off individual generators during partial load operation to raise the power of the remaining machines to full load operation. Due to the connection and disconnection of individual generators, the utilized capacity of the generators can be optimized and the efficiency can be increased. Further increase of the efficiency is expected for decoupling individual drive trains in the gearbox, especially for the gearbox configuration with the power split in the first stage (SPPP).

While start-up and full load operation is identical to the operating strategy of conventional WTs, the strategy during partial load operation has to be extended. Using six generators the partial load operation needs to be divided into six individual operating areas. Each of these areas must be provided with both a speed control and a pitch control strategy, in order to protect the WT during short-term changes of the wind speed. The possible ranges of operation during partial load operation are dependent on the torque characteristics of the electric machines and are limited by the rated torque. In Image 7 the torque characteristic of the WT rotor, based on the optimum tip speed ratio λ_{opt}, is shown, with the inevitable switching points of the individual generators. When the rated torque T_{Rated} of a generator is reached, another generator must be connected. This leads to the indicated switching points and the corresponding duty cycles of the generators. The partial load operation is most relevant for the overall energy yield, since about 70 % of the time the average wind speeds at which the WT usually operates are given during partial load operation, for both high and low wind sites. A uniformly distributed capacity, connection and disconnection of all the six generators results in a significant saving in full-load hours per generator for the total service life of 20 years intended for WTs.



$$\frac{P_{G,i}}{P_{Rated}} = \frac{n_i \cdot T_{Rated}}{n_{Rated} \cdot T_{Rated}} = \frac{n_i}{n_{Rated}}$$

$$P_{Rated,1} = 1MW \quad n_1 = 2452\ \mathrm{min}^{-1} \Rightarrow \frac{P_{G,1}}{P_{Rated,1}} = 49\%$$

$$P_{Rated,2} = 2MW \quad n_2 = 3468\ \mathrm{min}^{-1} \Rightarrow \frac{P_{G,2}}{P_{Rated,2}} = 69\%$$

$$P_{Rated,3} = 3MW \quad n_3 = 4247\ \mathrm{min}^{-1} \Rightarrow \frac{P_{G,3}}{P_{Rated,3}} = 85\%$$

$$P_{Rated,4} = 4MW \quad n_4 = 4904\ \mathrm{min}^{-1} \Rightarrow \frac{P_{G,4}}{P_{Rated,4}} = 98\%$$

$$P_{Rated,5} = 5MW \quad n_5 = 4978\ \mathrm{min}^{-1} \Rightarrow \frac{P_{G,5}}{P_{Rated,5}} = 99.5\%$$

$$P_{Rated,6} = 6MW \quad n_6 = n_{Rated} = 5000\ \mathrm{min}^{-1} \Rightarrow \frac{P_{G,6}}{P_{Rated,6}} = 100\%$$

Image 7: Torque characteristic of the WT and duty cycles of the generators

8 Conclusions

This paper proposes an alternative drive train configuration with six high-speed generators (rated at 1 MW and 5000 min^{-1}) for a 6 MW WT. Four gearbox concepts and three electrical machines have been investigated, in order to determine the potential of a power density and an efficiency increase, as well as that of an investment cost reduction.

The dimensioned gearbox configurations show that with a higher modularity of the concepts, a reduction of weight and efficiency comes along. The investigated generators are smaller and have a higher power density when compared to the more conventional electrical machines for WT. Simulation results for the entire drive train with the V-PMSM as generator show an overall efficiency during full load operation of 91.42 % for the WT with a SPPP gearbox and 91.50 % for the concept with a PPPS gearbox. During partial load, the efficiency of the drive train with a PPPS gearbox is up to 2 % higher, provided that no decoupling of individual drive train is considered.

In future works the efficiency simulation model will be extended with the discussed operating strategy. With the possibility to switch several generators off, as well as to decouple individual drive trains of the gearbox during partial load operation, a significant efficiency increase is expected. Furthermore, the SCIM and EESM electrical machine configurations will be designed numerically with FEM calculations, in order to improve the analytical results and to use them for ensuing efficiency simulations. Based on the dimensions and efficiency results of the different configurations, a WT drive train concept will be selected for the future detailed design process.

9 Bibliography

[AND80] N. E. Anderson, S. H. Loewenthal:
Spur-Gear-System Efficiency at Part and Full Load
NASA Technical Paper 1622, Technical Report 79-46, 1980

[BER11] J. Berroth:
Design and Modelling of the structural components of an offshore wind energy plant for multibody simulation
Diploma thesis, 2011

[CLI08] Clipper Windpower:
Liberty 2.5 MW Wind Turbine
http://geosci.uchicago.edu/~moyer/GEOS24705/Readings/Liberty_Brochure_2009_LR.pdf (December 2014)
Product brochure, 2008

[EGG12] D. Eggers, S. Steentjes, K. Hameyer:
Advanced Iron-Loss Estimation for Nonlinear Material Behavior
In: IEEE Transactions on Magnetics, vol. 48, no. 11, pp. 3021−3024, 2012

[FIN10] T. Finken, M. Hombitzer, K. Hameyer:
Study and Comparison of several Permanent-Magnet excited Rotor Types regarding their Applicability in Electric Vehicles
In: Emobility – Electrical Power Train, pp. 1−7, VDE, Leipzig, 2010

[GAS11] R. Gasch, J. Twele:
Windkraftanlagen. Grundlagen, Entwurf, Planung und Betrieb
Vieweg und Teubner, Wiesbaden, 2011

[HAN12] T. Hang:
Compact Drive Trains Offer New Options
http://www.renewableenergyworld.com/rea/news/article/2012/04/compact-drive-trains-offer-new-options (December 2014)
Internet article, Renewable Energy World, 2012

[KNO10] U. Knoedel, A. Strube, U. Blessing, S. Klostermann:
Auslegung und Implementierung bedarfsgerechter elektrischer Antriebe
In: Automobiltechnische Zeitschrift, vol. 112, no. 6, Springer, 2010

[LIN10] H. Linke:
Stirnradverzahnung. Berechnung – Werkstoffe – Fertigung.
Hanser, München, 2010

[MÜL08] G. Müller, K. Vogt, B. Ponick:
Berechnung elektrischer Maschinen
Wiley-VCH, Weinheim, 2008

[SAE09] Schaeffler Gruppe Industrie:
Großlagerkatalog
Firmenschrift, 2009

[WIN14] Winergy Drive Systems:
Multi Duored Gearbox
http://www.winergy-group.com/root/img/pool/downloads/en/product-brochure-multi-duored-gearbox-winergy.pdf (December 2014)
Product brochure, 2014