Alternative Wind Turbine Drive Train with Power Split and High-speed Generators

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Motivation and Approach

Conventional wind turbines (WT) still have a lot of disadvantages, like large weight and size or poor efficiency and reliability. To reach a higher efficiency at a high power density, as well as reduce downtimes and improve maintenance, an alternative 6 MW WT drive train is developed. The proposed drive train has six 1 MW generators that rotate at 5000 rpm and thus combines the advantages of WTs with power split with the high-speed technology of electrical machines. Different gearbox configurations and generator topologies are designed and an operating strategy is developed.

Gearbox Configurations

Four gearbox configurations are designed and investigated on a concept level. They are composed of four gear stages to realize a ratio of over 1:400 for the high-speed generators. Three planetary gear stages (P) and one spur gear stage (S) are used to implement the power split to six generators. The differences between the individual concepts is the position of the power split to the six output shafts (see Figure 1). After the spur gear stage six switchable clutches are integrated, one for each gear train. The idea is to connect and disconnect individual generators and gear trains during partial load to increase the efficiency and optimize the capacity of the components.

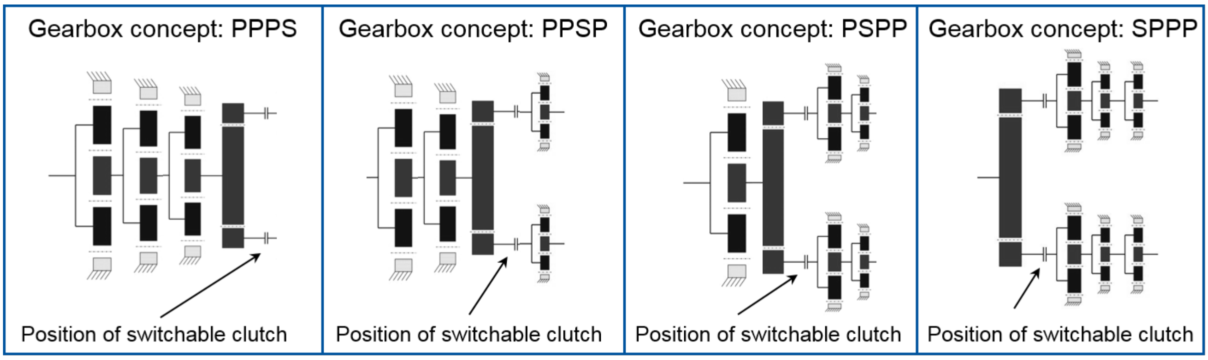

Figure 1: Gearbox configurations.

The comparison of the four configurations shows advantages for the SPPP concept, regarding weight and modularity (total number of parts to different number of parts) (see Table 1). The high number of identical parts with less weight enables a very modular gearbox design.

Gearbox concept	PPPS	PPSP	PSPP	SPPP
Weight (Gears, shaft, bearings)	≈ 47 t	≈ 49 t	≈ 45 t	≈ 40 t
Size (Width × length)	3.4 × 3.4 m	3.4 × 3.4 m	3.4 × 3.2 m	4.2 × 3 m
Total number of parts	90	193	275	370
Number of different parts	28	31	30	31
Modularity	3.21	6.23	9.17	11.94

Table 1: Comparison of different gearbox concepts.

Furthermore, due to the integration of switchable clutches immediately after the first gear stage, the SPPP concept offers the greatest potential to improve the utilization capacity and to increase the efficiency during partial load operation (see section “Operating Strategy”).

Generator Topology

Different electrical machines are evaluated, in order to choose the most suited topology for the application as a high-speed WT generator. The evaluation is based on the Esson power coefficient C, which can help determine the utilization of an electrical machine. The Esson coefficient sets a direct relation between the power that can be obtained from an electrical machine and its volume and speed. It can be calculated based on the rotational thrust of the machine σ, which is a design dependent quantity and can therefore be used to compare different machine topologies. The rotational thrust is given by the tangential component of the magnetic field strength H_t (which is equivalent to the current distribution A) and the normal component of the magnetic field induction B. Table 2 shows the rotational thrusts and the Esson coefficients for different electrical machines. Typical values for other machine parameters (power factor $cos\varphi$, winding factor ξ and efficiency η), further needed for the calculation of the rotational thrust, are given as well. The synchronous machine with permanent magnet excitation (PMSM) displays the highest power density.

Electrical machine	**Typical values**		**Rotational thrust [kN/m²]**	**Esson power coefficient [kW·min/m³]**
Squirrel cage induction machine SCIM	A = 40 000 A/m B = 0.8 T	$cos\varphi$ = 0.85 ξ = 0.95 η = 0.95	17.4	2.86
Electrically excited synchronous machine EESM	A = 40 000 A/m B = 1.2 T	$cos\varphi$ = 0.90 ξ = 0.95 η = 0.96	27.8	4.57
Permanent magnet synchronous machine PMSM	A = 40 000 A/m B = 1.2 T	$cos\varphi$ = 0.90 ξ = 0.95 η = 0.97	28.1	4.62

Table 2: Rotational thrust and Esson power coefficient for different electrical machines.

The PMSM also has the highest efficiency, since no copper losses occur, due to the fact that the excitation is provided through permanent magnets and no copper winding is necessary. Both synchronous machines (PMSM and EESM) display higher efficiency in the low speed range, while the induction machine (SCIM) has an efficiency advantage in the field-weakening area (see Figure 2).

Since the targeted speed of the generator for the developed WT drive train concept is higher than that of conventional machine topologies, further requirements have to be regarded. Especially the mechanical stress on the rotor of the machines due to centrifugal forces has to be accounted for. For the proposed application, the circumferential speed should not exceed 100 m/s, which constraints the maximum radius of the rotor at 0.19 m (for the given speed of 5000 rpm). The mechanical stress can also show local hot-spots, depending on the geometry. In the case of the PMSM for instance, higher stress occurs in the iron bridges around the permanent magnet slots. On the other hand, the rounded shape of the rotor cage bars is of some advantage for the SCIM at higher speeds.

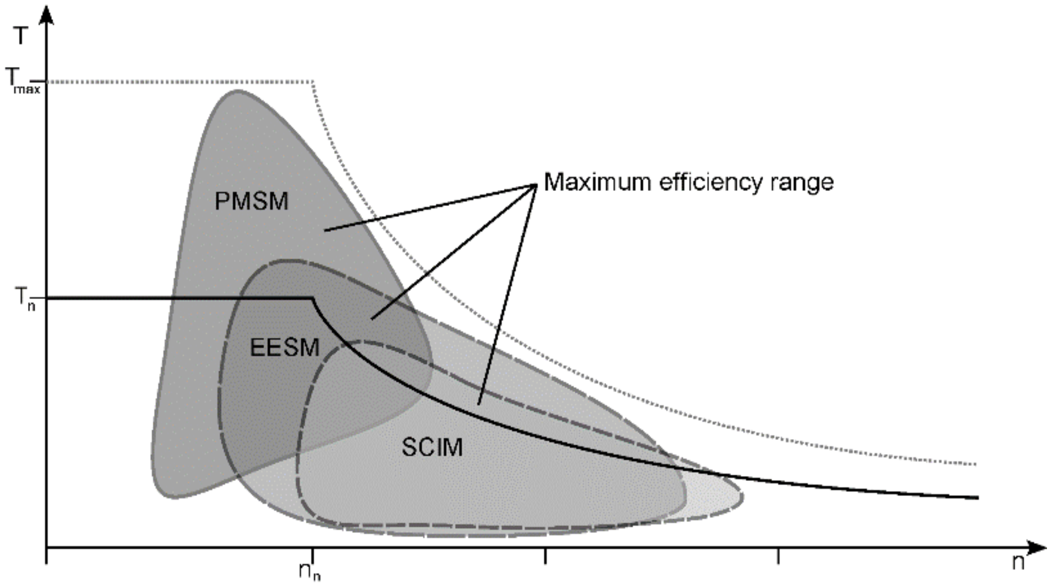

Figure 2: Exemplary efficiency ranges for different electrical machine topologies.

The evaluation and comparison of the different electrical machines sets the base for the subsequent, more detailed design study, for which the PMSM and the SCIM are regarded. For the PMSM an existing design with V-shaped internal magnets (V-PMSM) is scaled for the power of 1 MW and the speed of 5000 rpm and its efficiency map is determined with the help of the finite element method (see Figure 3). The resulting design has a volume of 0.1104 m^3, a power density of 9.06 MW/m^3 and a maximum efficiency of 98.6 %. The SCIM is initially designed based on analytical methods. The results for both machine concepts are shown in Table 3.

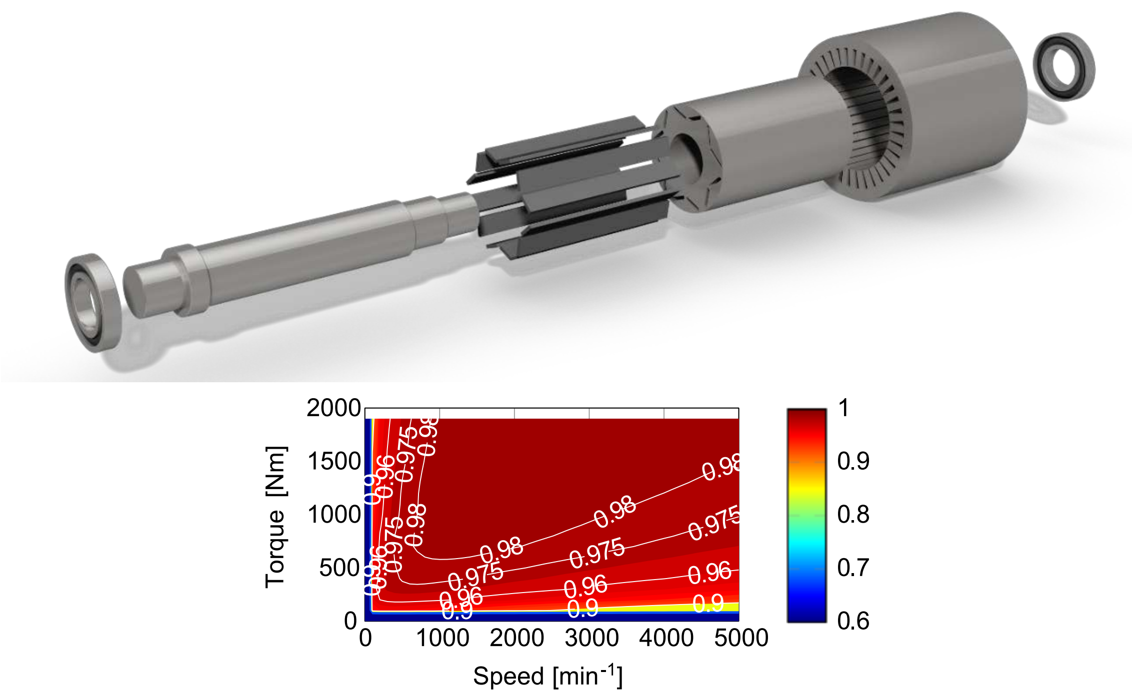

Figure 3: CAD model (exploded view) and efficiency map of the V-PMSM.

Electrical machine	SCIM	V-PMSM
Outer diameter	478.23 mm	480.00 mm
Total length (incl. end winding)	621.26 mm	610.00 mm
Volume	0.1116 m^3	0.1104 m^3
Power density	8.96 MW/m^3	9.06 MW/m^3
Efficiency	95 %	98 %

Table 3: Comparison of the considered electrical machine concepts.

Operating Strategy

The operating strategy of the proposed drive train concept is identical to conventional WTs during full load operation, but extended for partial load operation with the possibility to connect and disconnect individual gear trains and generators. The partial load operation needs to be divided into six individual operating areas. The torque characteristic of the WT, based on the optimum tip speed ratio λ_{opt} and the rated torque of the generators, determines the switching points to connect or disconnect individual generators. To evaluate the potential of an efficiency increase, an efficiency simulation model is created. In the simulation model the main bearing, the SPPP gearbox concept and six V-PMSM generators are considered (see Figure 4). The calculation of the power losses is based on [SAE09] for the bearings, on [AND80] and [NIE89] for the gear meshing and on [LIN10] for the seals. The losses of the generators are determined from the characteristic efficiency diagram of the V-PMSM configuration (see section "Generator Topology"). Based on the average wind speed, the power losses of the drive train can be calculated for every operating point.

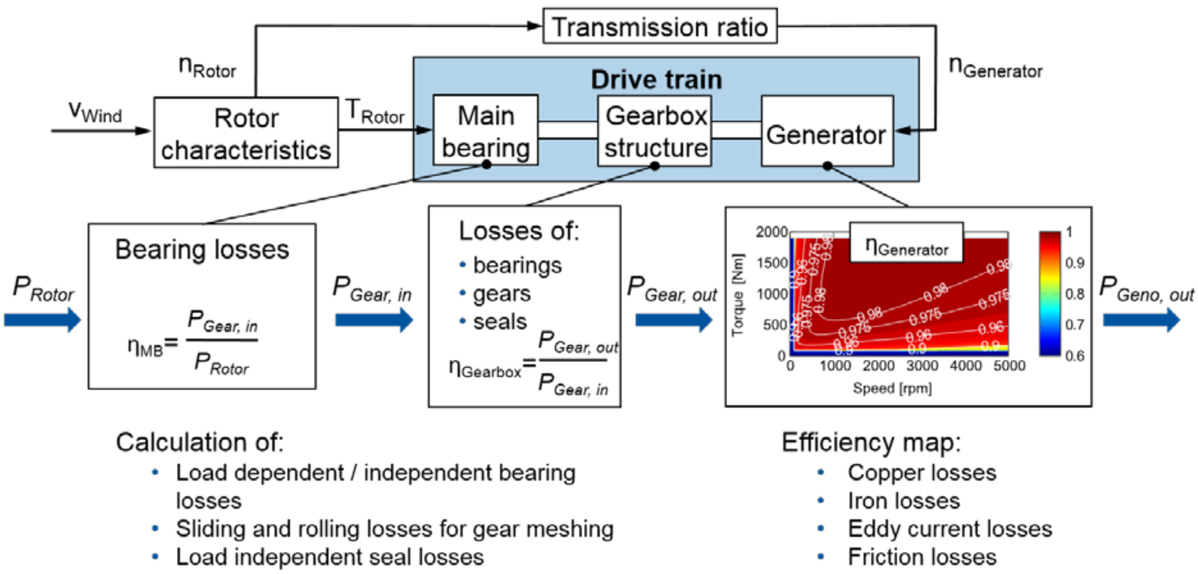

Figure 4: Efficiency simulation model.

The results show a rise of the efficiency curve from the partial to the full load range, with a maximum efficiency of about 93.5 % at full load (see Figure 5). Implementing an operating strategy with individual connection of generators shows an efficiency increase in the lower range of the partial load operation. As soon as all generators are switched on (at approximately 83 % rated power), the efficiency curve follows the same path as in the case where no switching procedure is used.

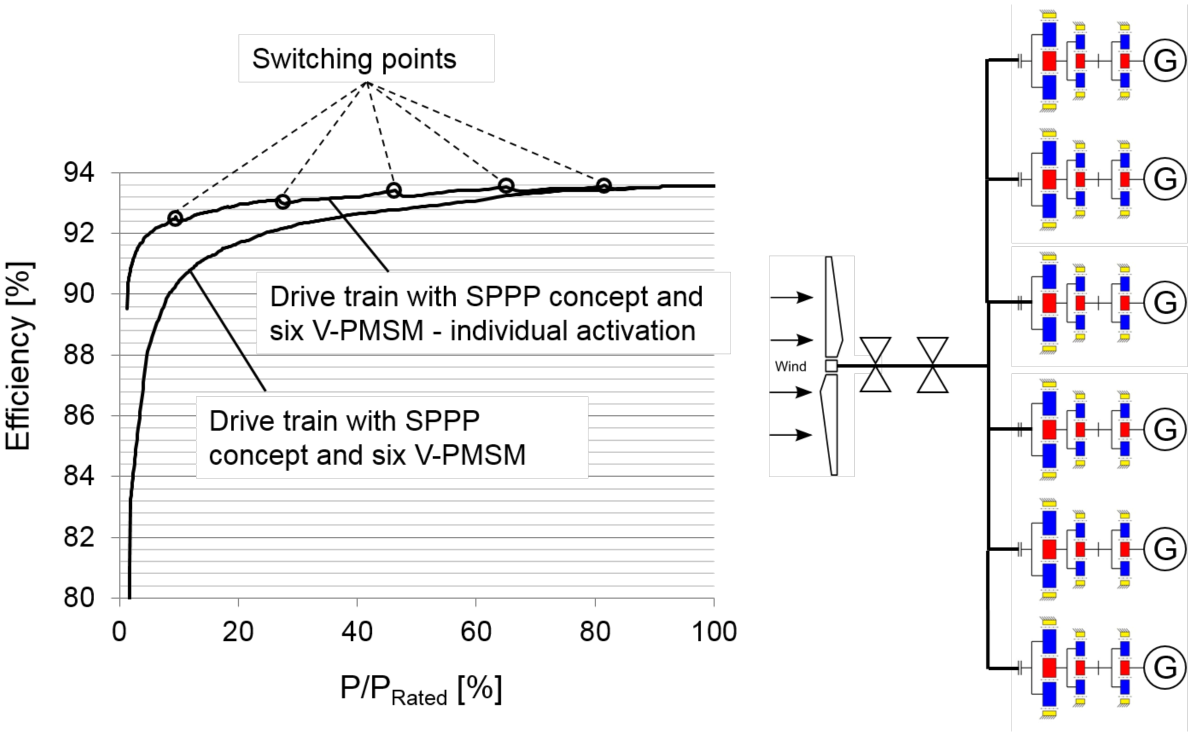

Figure 5: Efficiency calculation results.

Conclusion

In this paper an alternative drive train configuration with six high-speed generators (rated at 1 MW and 5000 rpm) for a 6 MW WT was developed. Different gearbox concepts and electrical machines have been investigated, in order to determine the potential of a higher power density and an efficiency increase. The SPPP gearbox configuration shows advantages regarding both weight and modularity. Efficiency simulation models for the entire drive train were created, considering a V-PMSM topology as a generator. Simulation results display an efficiency increase of up to 7 % during partial load operation, provided that an operating strategy is considered, where gear trains and generators are individually connected and disconnected.

Learning Objectives

The results for the SCIM topology shown in section “Generator Topology” were achieved based on rough analytical design methods. A more detailed model assuming higher harmonics will be used ([OBE93], [OBE07]), in order to assure a fair comparison to the V-PMSM, for which a much higher detail depth was achieved with the help of the finite element method.

Subsequently, based on the dimensions and efficiency results of the different gearbox and generator configurations, a final WT drive train concept will be selected for the structural-dynamic design process.

References

[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.

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

[NIE89] G. Niemann und H. Winter:
Maschinenelemente, Band II, Getriebe allgemein, Zahnradgetriebe – Grundlagen, Stirnradgetriebe.
Springer, Berlin, Heidelberg, New York, London, Paris, Tokyo, 1989.

[OBE93] K. Oberretl:
Allgemeine Oberfeldtheorie für ein- und dreiphasige Asynchron- und Linearmotoren mit Käfig unter Berücksichtigung der mehrfachen Ankerrückwirkung und der Nutöffnungen, Teil I und II.
Archiv für Elektrotechnik, Vol. 76, 1993.

[OBE07] K. Oberretl:
Losses, torques and magnetic noise in induction motors with static converter supply, taking multiple armature reaction and slot openings into account.
IET Electric Power Applications, Vol. 1, Nr. 4, pp. 517-531, 2007.

[SAE09] Schaeffler Gruppe Industrie:
Großlagerkatalog.
Firmenschrift, 2009.