Coil Excited Magnetic Gears for Large Wind Turbines

Andreas Penzkofer, Kais Atallah, and Milijana Odavic
Department of Electronic and Electrical Engineering, University of Sheffield, UK

Introduction

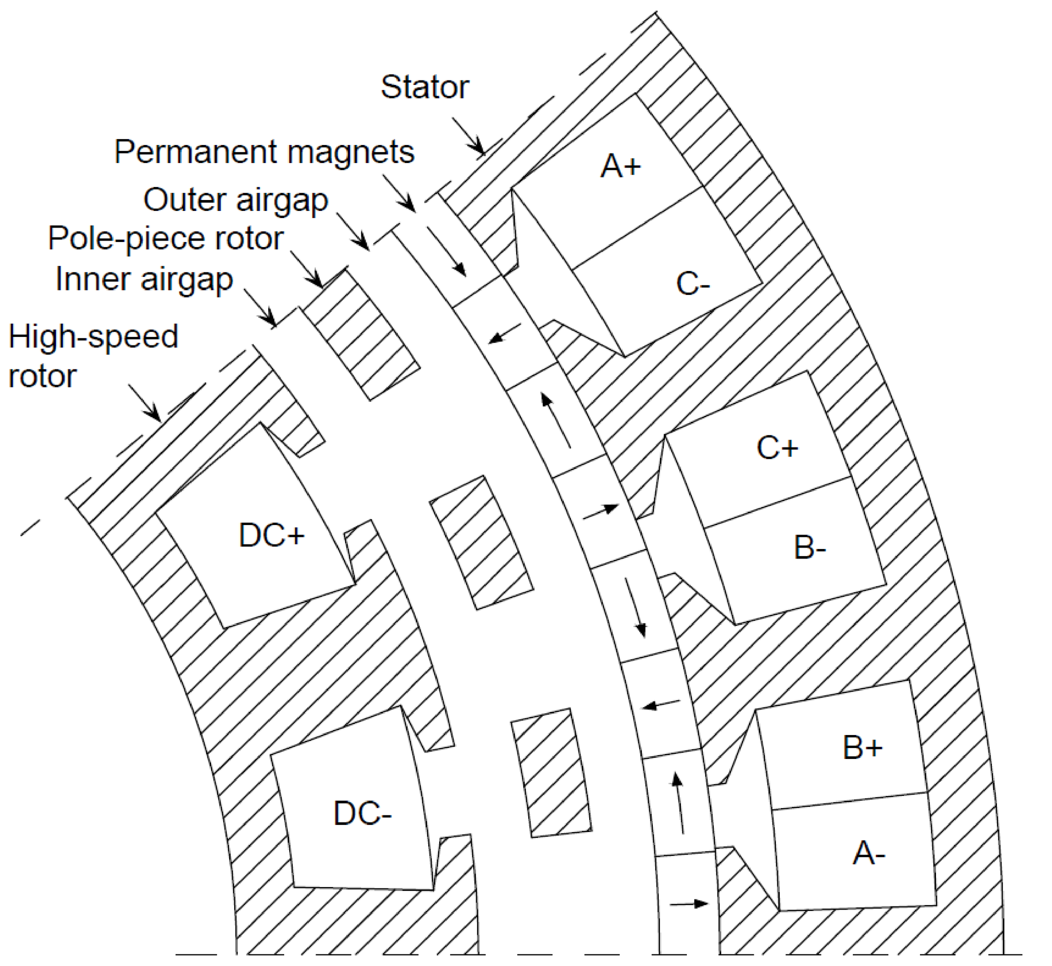
Magnetic gears can be an alternative solution to mechanical gears in wind turbine drive trains. Because of the contactless torque transmission capability and the inherent overload protection, reliability can be significantly improved [1]. Furthermore, stator windings may be added to form a Pseudo-Direct Drive (PDD) [2], which could enable the realisation of compact and light-weight drive-train solutions for wind turbines [3].

Despite their many advantages a drawback remains the large volume of permanent magnets (PM) required for their realisation [4]. Therefore, it is proposed that in order to reduce the PM mass and introduce an extra degree of controllability, that the HS rotor is excited using coils supplied with a DC current. This work is an investigation into the performance of coil excited PDDs for large wind turbine applications. Analytical techniques have initially been employed for the investigation of the effects of the key design parameters [6]. However, two designs have been selected for a more detailed analysis, using finite element method. These designs have then been utilised to investigate into the effects of the the control strategy on the efficiency of the PDD.

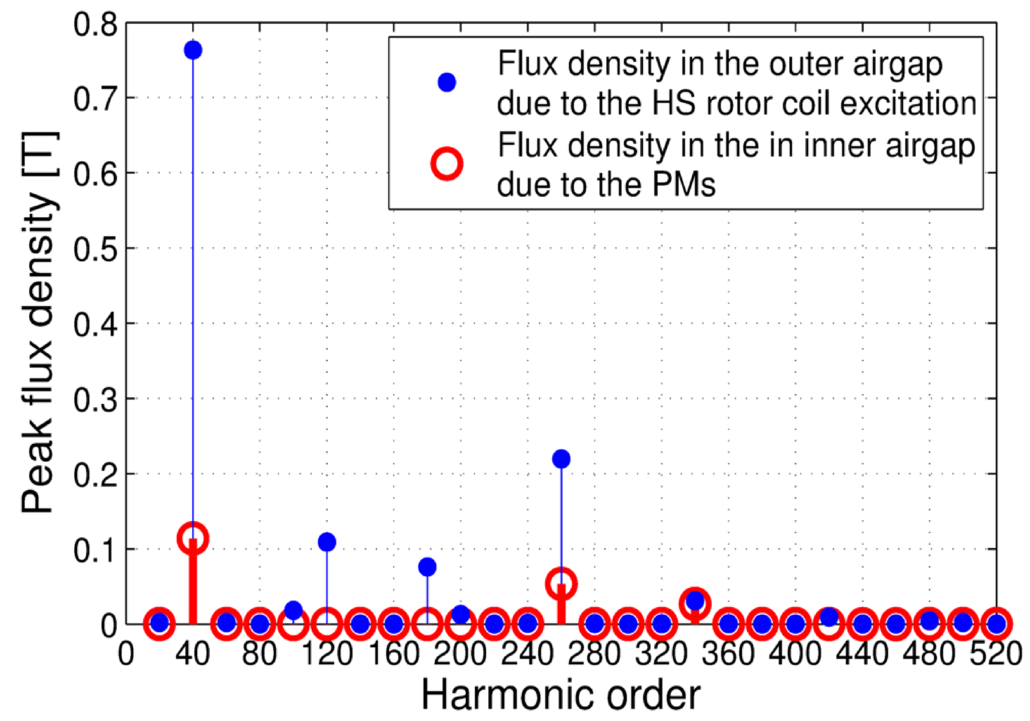
Parameters of the PDDs for a 10MW wind turbine

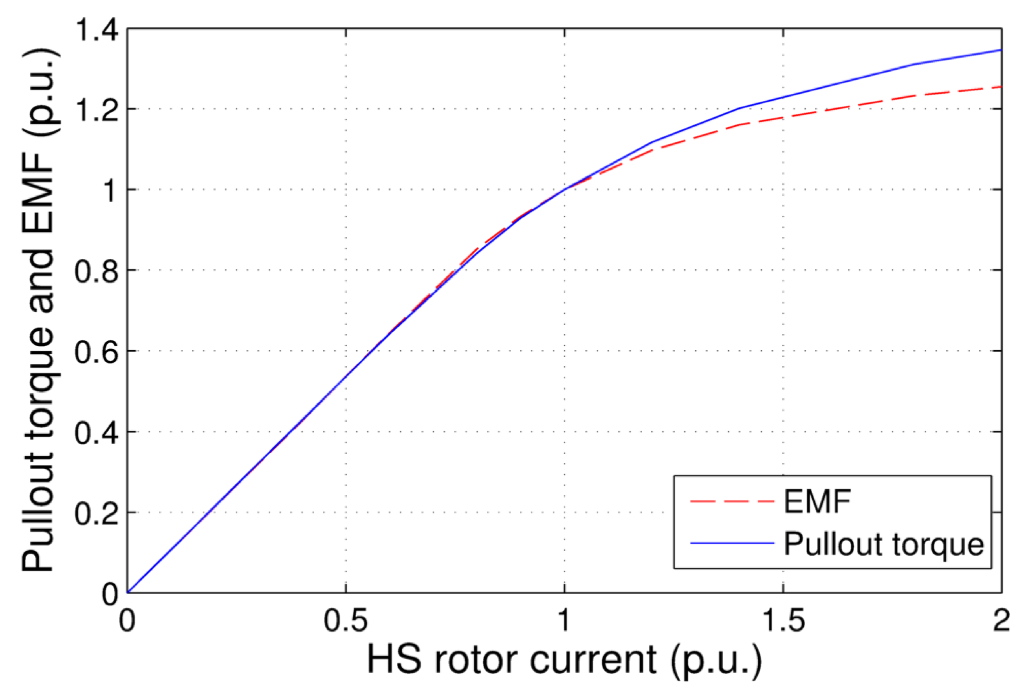
Quantity	PDD 1	PDD 2
Pull-out torque [MNm]	11.9	11.9
Gear ratio	7.5	7.5
Pole pairs (high-speed rotor)	40	40
Pole pairs (low-speed rotor)	260	260
Pole pieces	300	300
Remanence of the magnets [T]	1.25	1.25
Rated speed of PP rotor [rpm]	9.6	9.6
PM mass [tons]	4.5	4
Copper mass [tons]	20	17
Active steel mass [tons]	59	62
Efficiency at rated power [%]	95	95

Principle of operation



- The windings on the HS rotor interact with the windings on the stator to produce electromagnetic torque.
- The torque on the HS rotor is transferred to the pole-piece rotor by the interaction of the windings on the HS rotor and the permanent magnets on the stator.
- The pullout torque T_{pull} and the EMF are dependent on the HS rotor dc current I_f.





Variation of EMF and pullout torque with the HS rotor excitation current. (Values are shown per unit of rated value)

Control of the PDD

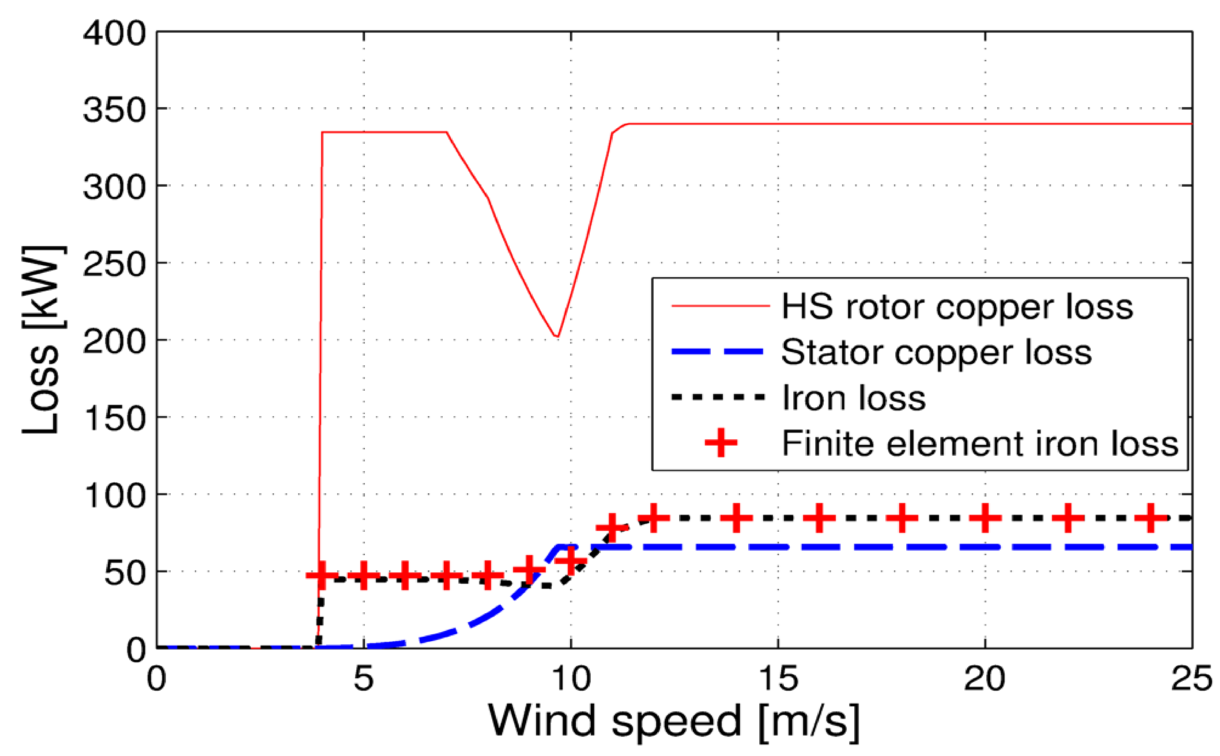
The coil excited high-speed rotor can be actively controlled so as to minimize the electromagnetic losses, while satisfying the operational requirements/constraints as follows:

$$T_{pull} \geq 1.2 \times \text{turbine torque} \qquad I_S \leq \text{rated stator current}$$
$$EMF \geq \text{minimum } EMF \qquad I_f \leq \text{rated HS rotor current}$$

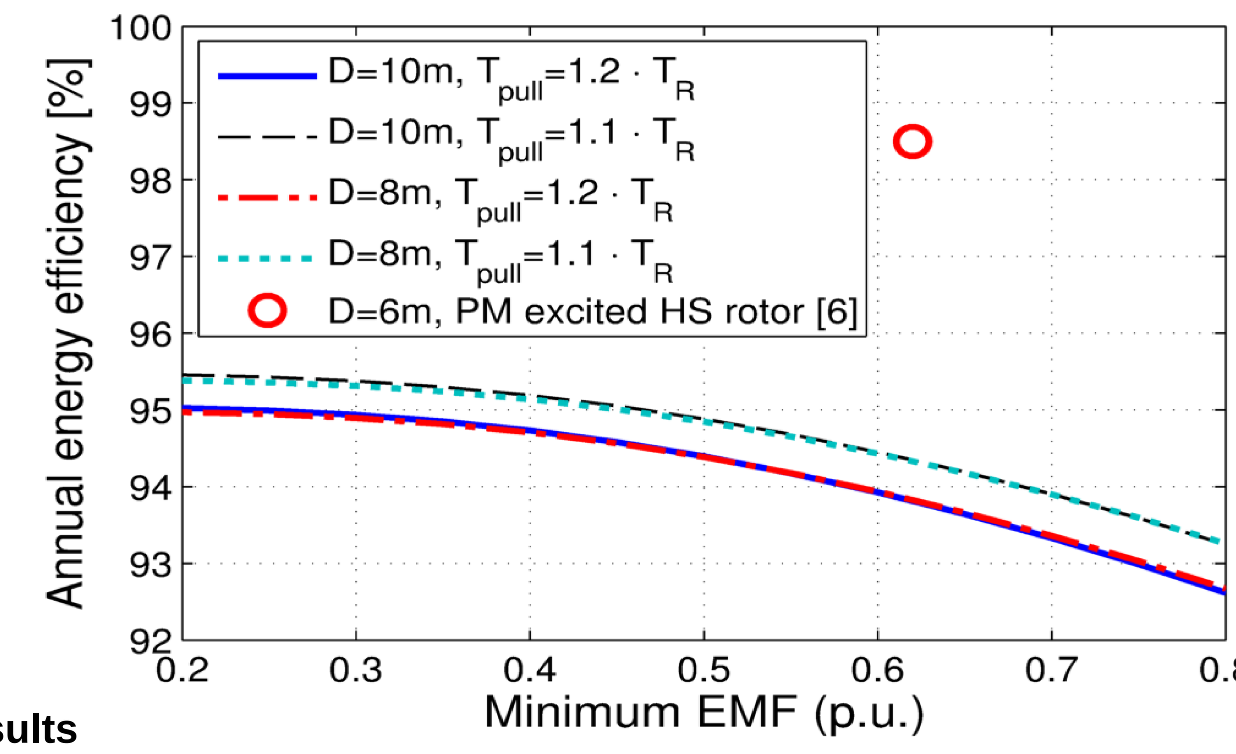
Loss analysis

In order to avoid time consuming finite element analysis the iron losses have been assumed to be given by the following analytical expression of I_f, I_S and the rotational speed Ω:

$$P_{iron}(I_f, I_S, \Omega) = \Omega\,(c_{h,f} I_f^2 + c_{h,S} I_S^2) \quad \text{(hysteresis)}$$
$$+\Omega^2 (c_{c,f} I_f^2 + c_{c,S} I_S^2) \quad \text{(classical eddy currents)}$$
$$+\Omega^{1.5} (c_{e,f} I_f^2 + c_{e,S} I_S^2)^{0.75} \quad \text{(excess eddy currents)}$$



The annual energy efficiency is calculated by employing a Weibull probability distribution that has been fitted to a measured wind profile [5].



Results

- An active DC control allows for the employment of a passive diode rectifier, resulting in less costly, simpler and more reliable power electronics than if a active rectifier is employed.
- The efficiency can be improved if the PDD is allowed to operate closer to the pullout torque.
- The selection of the minimum EMF has a significant effect on the annual energy efficiency and this should be considered, when a control strategy and a converter topology are selected.

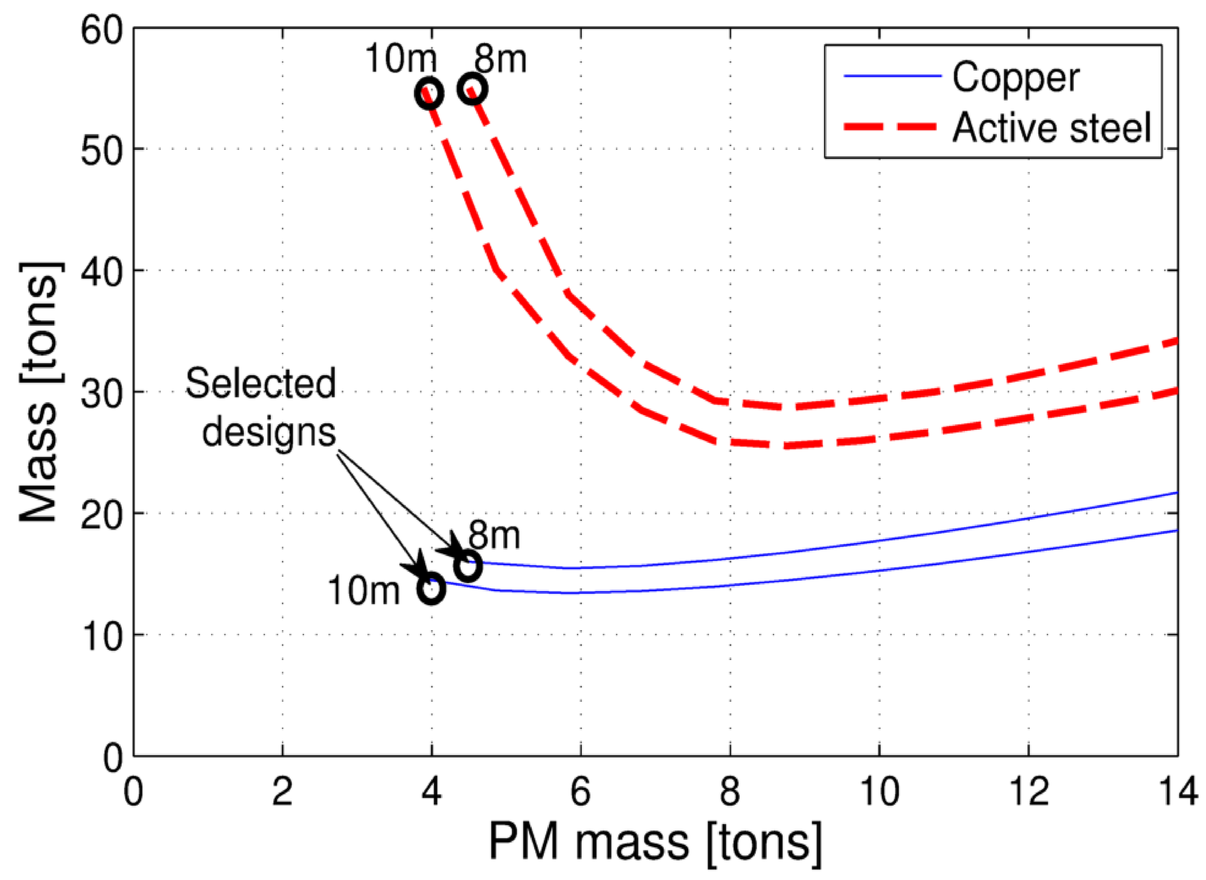
Design of a 10MW PDD

Design analysis using analytical methods:

- Analytical techniques developed for the prediction of the flux density distribution in PDDs with PM excitation [6] have been extended to accommodate the HS rotor windings.
- Effects of the leading design parameters on the active masses and the efficiency have been investigated.

Results

- A minimum PM mass is required to avoid saturation in the HS rotor teeth.
- For a larger diameter a lower PM mass may be required



Variation of active masses with the PM mass, when the axial length is fixed and the copper loss is fixed to 4.0%.

Since the analytical method doesn't take into account of saturation, finite element has subsequently been used in order to further optimize the two selected designs shown in the table.

Conclusion

A PDD with coil excited HS rotor has been presented. It has been shown, that when applied to a 10MW wind turbine, significant reductions in PM mass can be achieved, albeit at the expense of increased total active mass and reduced efficiency. It is also shown that the control strategy, more specifically the variation of the DC excitation current with wind speed, can result in significant improvements in efficiency.

[1] K. Atallah and D. Howe, "A novel high-performance magnetic gear", *IEEE Trans. Magn.*, vol. 37, no. 4, pp. 2844 --2846, Jul. 2001.
[2] Atallah, K. and Rens, J. and Mezani, S. and Howe, D., "A Novel 'Pseudo' Direct-Drive Brushless Permanent Magnet Machine", *Magnetics, IEEE Transactions on Magnetics* 44, 11 (2008), pp. 4349 -4352.
[3] H. Polinder, J. Ferreira, B. Jensen, A. Abrahamsen, K. Atallah, and R. McMahon, "Trends in wind turbine generator systems," *Emerging and Selected Topics in Power Electronics, IEEE Journal of*, vol. 1, no. 3, pp. 174–185, Sept 2013.
[4] A. Penzkofer and K. Atallah, "Magnetic gears for high torque applications," *Magnetics, IEEE Transactions on*, vol. 50, no. 11, pp. 1–4, Nov 2014.
[5] I. Bastigkeit, et.al. "Database of existing wind parameter measurements for tall atmospheres across Europe", INNWIND.EU, Work package 1: Conceptual designs, Task 1.1: External conditions, Report deliverable D1.11, Aug 2014.
[6] A. Penzkofer and K. Atallah, "Analytical modeling and optimization of pseudo-direct drive permanent magnet machines for large wind turbines," Magnetics, IEEE Transactions on, vol. 51, no. 12, pp. 1–14, Dec 2015.