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Magnet Free Generators - 3rd Generation Wind Turbine Generators

Bogi Bech Jensen, Nenad Mijatovic and Matthew Lee Henriksen
Department of Electrical Engineering, Technical University of Denmark, Denmark, bbj@elektro.dtu.dk

Abstract – **This paper presents an introduction to superconducting wind turbine generators, which are often referred to as 3rd generation wind turbine generators. Advantages and challenges of superconducting generators are presented with particular focus on possible weight and efficiency improvements. A comparison of the rare earth usage in different topologies of permanent magnet generators and superconducting generators is also presented.**

INTRODUCTION

The cost of energy from wind turbines at a good onshore site has become highly competitive with fossil fuel driven generation. However, it has become more difficult to obtain planning permission onshore, particularly near the shoreline where wind conditions are favourable. This is pushing operators to seek offshore sites, where planning permissions are easier to obtain.

Wind conditions are more favourable offshore which results in a higher capacity factor, meaning that each installed MW supplies more MWh on an annual basis. However, both installation costs and operating costs are higher offshore compared to onshore, which results in a higher cost of energy:

$$CoE = \frac{Annualised\ CAPEX\ and\ OPEX}{Annual\ energy\ production}$$

The main focus of the wind industry is therefore on reducing the capital expenditure (CAPEX) and operating expenditure (OPEX), as well as increasing the annual energy production and the lifetime of the wind turbine. As offshore installation and operation is very expensive it is more cost efficient to install fewer larger wind turbines instead of installing many smaller wind turbines. This has led to most of the wind turbine manufacturers proposing offshore wind turbines that are larger than 5 MW, table 1, and some investigating possibilities of going beyond 10 MW, table 2.

The drive train of a 10MW wind turbine using traditional technology will weigh more than 300 tons and will use in the order of 8-10 tons of rare earth magnets if direct drive permanent magnet generators are employed. If superconducting technology is employed the weight can be halved to 150 tons and the rare earth usage can be eliminated [1] and [2].

Table 1 – Overview of manufacturers going beyond 5 MW

Manufacturers	Transmission	Generator
Siemens Wind Power	Direct drive	PMSG 6.0 MW
Vestas	Medium speed	PMSG 8.0 MW
Enercon	Direct drive	EESG 7.5 MW
Alstom	Direct drive	PMSG 6.0 MW
REPower	High speed	DFIG 6.2 MW
Areva	Low speed	PMSG 5.0 MW

Table 2 – Proposed 10 MW superconducting wind turbines

Manufacturers	Transmission	Generator
American Superconductor	Direct drive	HTS 10 MW
General Electric	Direct drive	LTS 10 MW
Advanced Magnet Lab	Direct drive	MgB2 10 MW
Tecnalia	Direct drive	MgB2 10 MW

SUPERCONDUCTIVITY

In a superconductor the resistivity is practically zero. This can only be achieved if the superconductor is operated within the critical limits of current density, flux density and temperature. If any of these limits is exceeded the superconductor becomes non-superconductive, which in the worst case can destroy the superconductor. Superconductors are classified as high temperature superconductors (HTS), which are typically operated at 30-50 K, low temperature superconductors (LTS), which are typically operated at 4 K, and MgB2, which is typically operated at 15-20 K.

SUPERCONDUCTING GENERATORS

A superconducting generator has at least one superconducting coil. This coil can be placed on the rotor, the stator or both rotor and stator. Most commonly proposed superconducting machines are wound field synchronous machines with superconducting field windings. Examples of such machines can be found in [1] and [2], where both American Superconductor (AMSC) and General Electric (GE) have proposed wind turbine generators with superconducting field windings. AMSC have proposed the SeaTitan, which is a wound field synchronous generator with HTS field windings on the rotor and stationary armature windings, figure 1. GE have investigated a 10 MW wound field synchronous generator with LTS field windings on the stator and rotating armature windings, figure 2.

Fully superconducting wind turbine generators have also been proposed by AML [3], where both armature and field windings are superconductive, figure 3. This has been proposed using MgB2, which has better ability to carry alternating currents compared to HTS and LTS.
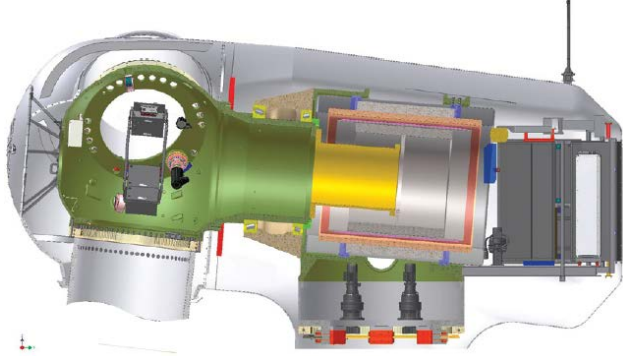

Figure 1 – 10 MW superconducting wind turbine generator with HTS field windings on the rotor and stationary armature windings (source: AMSC)
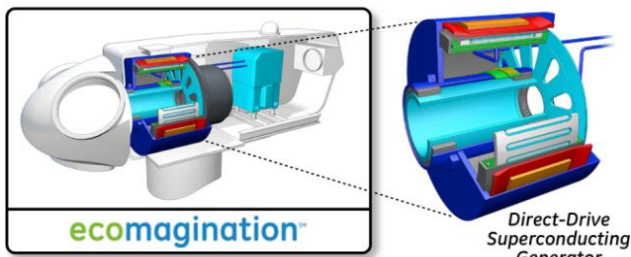

Figure 2 – 10 MW superconducting wind turbine generator with LTS field windings on the stator and rotating armature windings (source: GE)
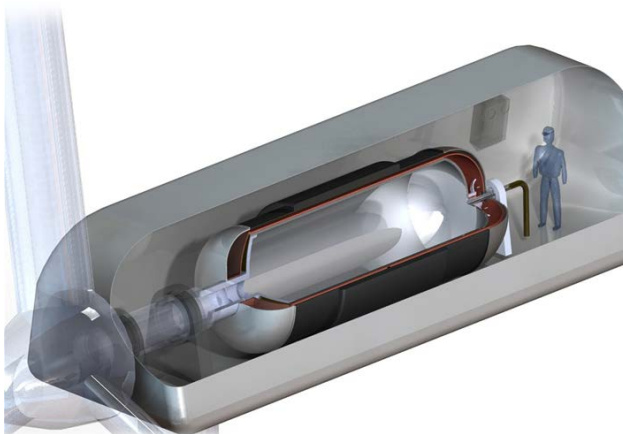

Figure 3 – 10 MW superconducting wind turbine generator with MgB2 superconductor on both field and armature windings (source: AML)

Partially superconducting generators, where only the field winding is superconductive, are expected to have torque densities that are double those of PM generators. Fully superconducting generators are expected to have 3-4 times the torque densities of PM generators. The reason for this is that the torque, T, in an electrical machine is proportional to electric loading, A, (the total armature current per meter circumference), the airgap flux density, B, and the airgap volume, V, meaning the volume of a cylinder with the diameter of the airgap and the length of the machine:

$$T \propto A \times B \times V$$

Since superconductors can carry very high currents (300 A/mm^2) with very little losses, the airgap flux density, B, can be increased by a factor of 2-3 compared to conventional machines. In a fully superconducting generator the electric loading, A, can also be increased

resulting in expected torque densities that are 3-4 times those of PM generators.

The efficiency of a superconducting generator is also expected to be higher than conventional machines including PM machines. The reason for this is that the armature losses, which are the dominating losses, are proportional to the current density and the volume of copper, hence if the armature current density is kept constant a smaller machine will have less copper and hence less losses. For a 10 MW direct drive wind turbine generator the full load armature losses of a PM generator can be expected to be 4.1% of rated power and 2.4% for a partially superconducting generator. In addition to this the superconducting generator will require in the order of 0.5% for cooling.

The challenges for superconducting wind turbine generators lie in the unknown and in the high cost of superconductors. There is no experience with superconducting offshore wind turbine generators and there is very limited experience with any kind of superconducting machine. The cold region has to be cooled to 4 K for LTS, 15-20 K for MgB2, and 30-50 K for HTS. Such temperatures require sophisticated cooling systems as well as insulation techniques, which both have to insulate and act as torque transfer elements. In addition the current production capacity for HTS is not sufficient for large scale production of superconducting wind turbine generators. A more thorough investigation of superconducting wind turbine generators is found in [4].

CONCLUSION

Superconducting wind turbine generators are expected to have 2-4 times higher torque densities compared to PM generators and could therefore be appropriate for future large offshore wind turbines. Superconducting generators are also expected to have higher efficiencies than PM generators, however the cooling and insulation systems as well as up scaling superconductor production pose significant challenges.

There is no standard for superconducting generators. The superconductor can be used on the stator, on the rotor, or on both stator and rotor. The superconductor is most often proposed for the field winding but it can also be placed in the armature winding. The path to commercialisation of superconducting wind turbine generators is therefore open.

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