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Design study of coated conductor direct drive wind turbine generator for small scale demonstration

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Abstract

We have investigated the properties of a superconducting direct drive generator suitable for demonstration in a small scale 11 kW wind turbine. The engineering current density of the superconducting field windings is based on properties of coated conductors wound into coils holding of the order 68 meters of tape. The active mass of the generators has been investigated as function of the number of poles and a 4 pole generator is suggested as a feasible starting point of an in-field demonstration of the system reliability. An active mass of m = 421 kg and a usage of 3.45 km of tape will be needed to realize such a generator with a peak flux density in the airgap of B_0 = 1.5 T.

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1. Introduction

Superconducting machines based on high temperature supercondcutors have been demonstrated for the application of ship propulsion [1], where the torque and speed are in the range of 2.9 MNm and 120 rpm. The application of direct drive generators for future large offshore wind turbines will however request an even higher torque approaching T = 10 MNm for a 10 MW turbine rotating at 10 revolutions per minute [2, 3, 4]. The majority of the Eu wind power capacity has been installed during the last decade and the average turbine size today is in the range of 3-4 MW [4]. Larger turbines of P = 5 MW tailed to the offshore application have been introduced by Repower and Areva, and the development of a 6 MW and 7 MW offshore turbine has been announced by major industrial players like Siemens and Vestas. This trend is a clear indication that the offshore turbine technology is deviation from the on-shore technology and that the development towards the 10 MW power range has been initiated.

A challenge of the offshore wind turbines is to provide a drive train with a sufficient reliability to comply with the targeted cost of energy, which is calculated as the sum of the installation and operation/maintenance (OM) cost divided by the energy produced during the 20 year life time. A fundamental choice of the drive train technology is if a gearbox is used to decrease the torque rating of the generator by increasing the rotation speed. A gearbox is relatively cheap but might break down and cause a higher OM cost. The hybrid drive trains have been suggested to use gear boxes with only 1 or 2 stages connected to a medium speed generator and finally the direct drive solution is omitting the gearbox completely with the generator connected directly to the turbine blades.

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1.1. Direct drive wind generators

Direct drive generators based on copper field windings and permanent magnets allready exist (Enercon, Goldwin and Siemens), but they tend to become heavy at large power ratings. Both the copper and PM direct drive generators will have a fundamental limitation of the magnetic flux density in the airgap, because the magnetic flux is enclosed in magnetic steel, which will saturate at B = 1.6-1.8 Tesla. This have a consequence on the torque T

$$T = \sqrt{2} B_0 A_S \pi r^2 L \cos(p\psi) \tag{1}$$

produced by a machine with a fundamental airgap flux density of $B(\theta) = B_0 \cos(p\theta)$, an electric current loading of $I_S(\theta) = A_S \cos(p(\theta - \psi))$, a pole pair number of p, an active airgap radius r, an active length L and an angular displacement between magnetic flux and electric loading distribution of ψ. The electric loading A_S of the stator of the copper and PM machines is also limited by the need to removed the Joule heating caused by the resistivity. It is therefore concluded that the only option of increasing the torque, if the limitation of B_0 and A_S are reached, is to increase the volume $V = \pi r^2 L$ of the machine. From an electromagnetic point of view it is preferred to increase the radius, because the torque scales as $T \sim r^2$, but from a mechanical point of view this impose a need for structural material to stabilize a large diameter ring. If this structure constitute a disk of a radius almost equivalent to r and a thickness $t_{disk} = \alpha r$ which is scaling linear with the size of the disk then the volume and mass of the support structure will scale as $V_{support} = m_{support} \sim r^2 \alpha r \sim r^3$. Thus the weight increase of the generator scales with a higher exponent than the torque. This is a challenge for the wind turbine application, because the top head mass of the nacelle will impose additional cost to the tower construction and make the installation more complicated.

1.2. Superconducting direct drive generators

The superconducting wind turbine generator offers the opportunity to exceed the limitation of the airgap flux density B_0 of conventional generators, because the generation of magnetic flux is decoupled from the generation of Joule heating $P_J = RI^2$ due to the low voltage drop along the superconducting wires. Superconductors are often characterized by a measured power law relation between the electric field E along a wire and the current I

$$E(I) = E_0 \left(\frac{I}{I_C(\mathbf{B}, T)} \right)^{n(\mathbf{B},T)} \tag{2}$$

where $I_C(\mathbf{B}, T)$ is the critical current, which will cause an electric field of $E_0 = 10^{-4} V/m$ along the conductor when exposed to an applied magnetic field $\mathbf{B}$ at the temperature T. The exponent n is characterizing how abrupt the electric field will change around I_C. From Eq. 2 it is seen that the power dissipation P_S of a superconducting field winding energized by a DC current I will be

$$P_S = \int_{l=0}^{L_S} E(l) I dl \tag{3}$$

where $E(l)$ is the electric field at the position l along the conductor of a total length of L_S. Thus the ratio I/I_C between the current and the critical current is determining the local power dissipation. One could also consider to increase the current loading A_S of the stator using superconductors, but the exposure to an AC magnetic field and current will impose additional losses, which might be reduced by using a conductor composed of thin filaments. The low efficiency of cryogenic cooling cycles is presently preventing the utilization of the fully superconducting generator.

This paper will discuss the possibility to install a small scale superconducting direct drive generator in a 11 kW wind turbine and if the magnetic flux density can be increased to the $B = 1.5$ Tesla range. The paper is organized in a section on the experimentally obtained engineering current densities J_e obtained in a series of HTS race track coils, a section describing a simple generator model used to examine the amount of HTS tapes needed and a discussion of the possibility to cool such a generator in the wind turbine using a cryocooler.

2. HTS race track coils

We have previous constructed a series of race track coils based on Bi-2223 (1G) as well as the RABIT type coated conductor and the obtained engineering critical currents densities in the range of $J_e = 62-89\,\mathrm{A/mm^2}$. Additional work has been done on the IBAD type of coated conductor coil, which have the potential to provide higher $J_e = 186\mathrm{A/mm^2}$ values due to the thinner tape and insulation [6]. Two coils have been made with the geometry shown in figure 1a. The coils design is based on a stainless steel former, which was insulated by glass fiber tape. The superconducting tape with an $I_C(77K, 0T) = 119$ A was wound onto the former and enclosed by a stainless steel frame to give mechanical support to the winding. The superconducting tape was insulated by a thin layer of epoxy prior to the winding and some of the insulation was removed by polishing with sandpaper in order to solder the beginning of the tape to an inner copper block acting as current lead. A thin copper foil was soldered to the superconducting tape approximately 10 cm after the soldering of the copper block after first removing some of the insulation with the sandpaper polishing in order to obtain a voltage probe for a 4 point measurement of the superconducting properties. The tape was wound onto the former until the thickness was 1 cm and another piece of copper foil was soldered to the tape providing a mid section voltage probe. An end section voltage probe was soldered to the end of the tape approximately 10 cm before the tape was soldered to the copper nose acting as the outer current lead. Thin copper wires were soldered to the copper foil voltage probes and connected to a circuit board at the side of the outer frame. A stainless steel lid was placed on top of the coil and the windings were mechanically fixed by vacuum impregnating the coil with epoxy. The epoxy was injected at $T = 60\,^oC$ and allowed to rest for 30 minutes before the pressure of the vacuum furnace was increase to 1 atm to collapse any bubbles. The epoxy was subsequently gelled at $T = 90\,^oC$ and cured at $T = 110\,^oC$ for 6 and 12 hours respectively. Excess epoxy around the mold was removed by a hammer and the coils was detached from the lid and base plate of the mold.

Figure 1b is showing the voltage drop between the two voltage probes at the outer and inner turn as well as between the mid and outer turn as the current is ramped up. An Agilent 34420A nano-voltmeter was used to measure the voltage drop and a HP 6031A power supply was used as current source. The first measurement indicates that a voltage drop between the inner and outer turn is observed allready at $I \sim 10A$, which is mush lower that expected from the I_C of the tape. Thus it is immediately concluded that the tape has been damaged during the manufacturing process. However only a voltage drop equivalent to the noise level of the voltmeter is observed between the outer to mid voltage probes as the current is increased to I = 40 A. This current level caused the inner section of the coil to quench and a degradation of the critical current of the coil was observed when repeating the measurement. By defining the critical current of the coil as the current when the voltage drop becomes $U_0 = E_0 L_S$ it is found that $I_C = 35$ A. Thus the coils did not confirm the high J_e potential, but the outer section must have $J_e > 59.5\,\mathrm{A/mm^2}$ and the final J_e could not be determined.

Properties	Tape width	thickness	Insulation thickness	$J_e(77K, 0T)$
IBAD tape	4.2 mm	0.1 mm	0.06 mm	$177.1\,A/mm^2$
Number of windings in coil	125			
Tape length in coil	68.5 m			
Coil obtained J_e	$> 59.5\,A/mm^2$			

Table 1. Properties of IBAD coated conductor and coil.

3. Generator model for the Gaia turbine

We have re-investigated a 11 kW Gaia turbine as a starting point of a small scale demonstration of a superconducting direct drive generator [5] by considering tape of the IBAD type. The turbine rating is P = 11 kW at a rotation speed of 56 rpm, which correspond to a torque of $T = P/\omega = 1.9\,\mathrm{kNm}$. By including a drive train loss of the order 10 % the mechanical torque provided by the generator should be of the order

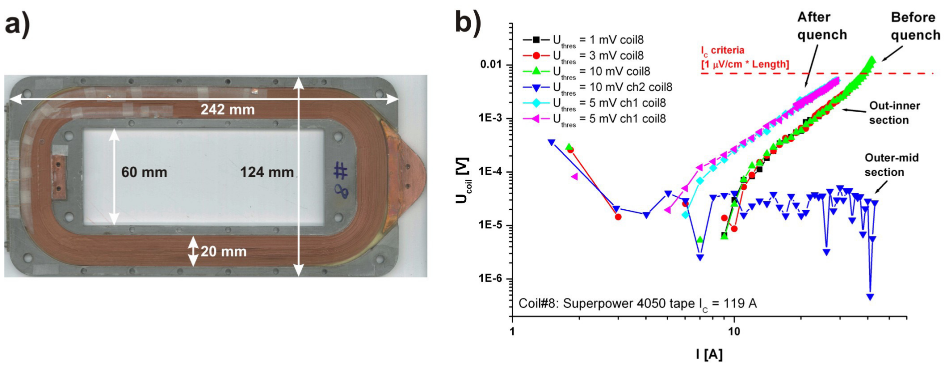

Fig. 1. a) Race track coil holding 68 m of IBAD type coated conductor wound on a steel former and enclosed by a steel frame. b) IV curve of the coils immersed in liquid nitrogen.

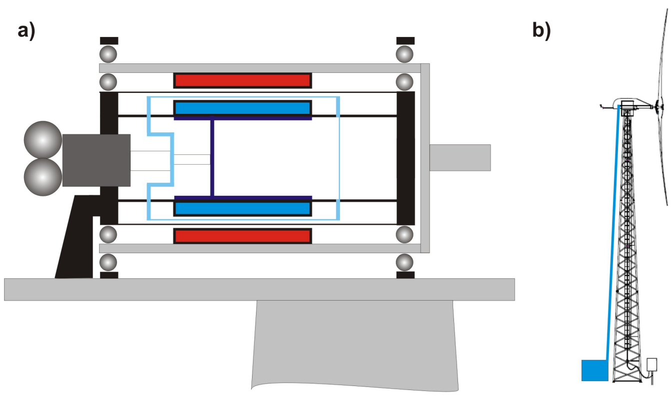

Fig. 2. a) Proposal of cryocooler installation in a direct drive generator, which will fit into b) the 11 kW Gaia wind turbine.

$T_m = P/\omega = 2.1$ kNm. The size of the Gaia nacelle will allow a generator with a diameter of the order 0.6 m and a total length of 1 m.

Figure 2a shows a possible layout of generator based on a cryocooler keeping a set of superconducting field windings cold in the middle of the machine. It is suggested that the cryocooler and superconducting coils are fixed to the bed plate of the nacelle and that the armature is rotated on a set of ball bearing. Sliprings connected to the armature are transferring the current to the nacelle. Figure 2b is showing the possibility to have the cryocooler coldhead at the top of the nacelle, the helium transfer lines mounted to the turbine tower and the compressor unit on ground resulting in a small extra weight load on the turbine.

3.1. Analytical flux circuit model

An analytical flux circuit model is used to determine the usage of active materials of the generator by specifying the reluctance $R_{r,c}$ in the radial and circumferential direction of the flux path [Abrahamsen2011]. The model result in a matrix relation between the magneto motive forces $\overline{F} = [0..F_S..0]$ and the flux $\overline{\phi} = [\phi_1...\phi_N]$ in the N different layers of a pole-pair

$$\overline{F} = \overline{\overline{M}}\,\overline{\phi} \tag{4}$$

where the magneto motive force of the superconducting coil is determined by the number of windings

N_S and the current I_S giving $F_S = N_S I_S$. The matrix $\overline{\overline{M}}$ is composed of the combinations of reluctance terms dictated by Kirchhoff's law[Abrahamsen2011]. By inverting 4 one can obtain the flux in the airgab ϕ_{airgap} of the machine and this can then be related to peak magnetic flux density B_0 in equation 1 by

$$\phi_{airgab} = \int_{\frac{\pi}{2p}}^{\frac{\pi}{2p}} B_0 \cos(p\theta) d\theta \quad (5)$$

The current of the superconducting tape was assumed to be $I = 105$ A giving a $J_e = 149\,\text{A/mm}^2$ using the insulation specifications of table 1. The properties of electric steel M800 was used to determine the relative permeability $\mu_r = 462$ in magnetic flux densities up to 1.5 T. All other materials were assumed to have $\mu_r = 1$. A cryostat of thickness $t_{Cryostat} = 2\,\text{cm}$ is assumed to surround the rotor steel, superconductor winding and support keeping them all cold at the operation temperature. The copper of the stator is loaded at a current density of $J_{Cu} = 2A/mm^2$ in order to allow non-magnetic structural material providing mechanical support to the windings. The resistivity of Copper is assumed to be $\rho_{Cu} = 2 \cdot 10^{-8} \Omega m$ and is used to estimate the stator Cu losses. The active mass of generators with different number of pole pairs were determined from the analytical model by requiring that the outer radius was 0.3 m, the produced torque was $T = 2.1$ kMm, the peak flux density $B_0 \sim 1.5$ T and that the Cu losses were below 5 %. The average flux density of the rotor and stator were evaluated from the flux model in order to determine if the electric steel was heavily saturated. Finite element simulations are ongoing to confirm the analytical results.

4. Results and discussion

The degradation of the tapes in the coils shown indicate that the potential of a high engineering current density due to the small tape thickness might be difficult to realize, because the superconducting film is less protected than in the coated conductors laminated by additional metal layers. There have been progress in the manufacturing of the coils, since coil ♯7 had both section showing a transition similar to the one on fig. 1, but coil ♯8 was only damaged in the inner part. From visual inspection of the coil it is clearly seen that the inner part is wound very tight, whereas the outer part contains some wobbling of the turns. These wobbling turns might prevent the build up of shear stress during the cooldown of the coil from $T = 110\,oC$ and to $T = 77\,K$ and thereby preventing a delamination of the superconducting film from the substrate. Additional stresses acting in the c-axis direction of the tape might be induced by the larger thermal contraction of the epoxy compared to the stainless steel former and also cause a delamination of the film. Further work and modeling is needed to clarify the cause of the degradation.

The high engineering current density is however quite attractive for the superconducting machine application and figure 3a shows how the geometry of the direct drive generator will change when the number of poles is increased when assuming an engineering current density of $J_e = 149\,\text{A/mm}^2$. It is seen that the stator core back can be made thinner as the pole number is increased, but at the expense of using more superconductors. Figure 3b shows the variation of the active mass of the machine as function of pole number. The advantage of the 4 pole machine is that only $m_{SC} = 11.8$ kg of coated conductor corresponding to $L_{SC} = 3.45$ km of tape will be needed, but the rotor steel core will almost fill up the inner part of the machine completely. The estimate of the total active weight is $m_{4pole} = 421$ kg, which should be compared to the $m_{gear+gen} = 300$ kg of the Gaia turbine. In case of the 10 pole machine one will need $m_{SC} = 40.5$ kg corresponding to 11.83 km of tape and the total active weight has been reduced to $m_{10pole} = 349$ kg, which is getting close to the mass of the Gaia gearbox and generator. Considerable space is available in the center of the 10 pole generator and the design starts to resemble the topology suggested for large generators [6]. We will recommend the 4 pole generator as the most feasible demonstrator, because it will be the cheapest and because the 10 kw power range is to small to illustrate the true technical potential such as low mass and volume compared to conventional drive trains. The 4 pole generator will however provide experience on how to integrate the cryogenic cooling system with the superconducting windings as shown on fig 2a and also give experience on the system reliability.

The cooling power needed from the cryocooler can be estimated from eq. 3, since the loss of the entire tape length if $I = I_C$ will be $P_0 = L_S E_0 I = 36.2$ W. This must be multiplied by a factor $(I/I_C)^n = (0.8)^{20} =$

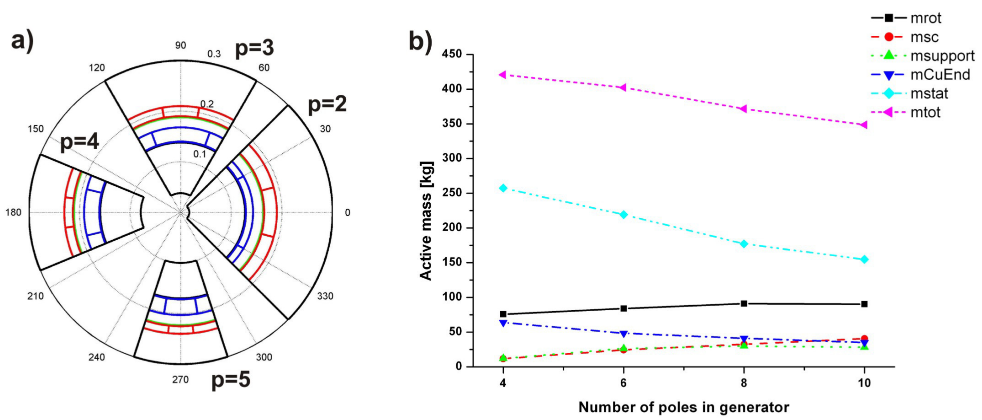

Fig. 3. a) Comparison of generators realized with different number of pole pairs $p = 2$ to 5 in order to provide a torque of $T = 2.1$ kNm, a peak airgap flux density of $B_0 = 1.5$ T, an outer diameter of $R_{out} = 0.3$ m and a loss in the stator copper limited to below 5 % of the turbine rating. The components shown form inside and out are rotor iron (black), superconductor (blue), cryostat (green), Airgap (green-red), Cu stator (red) and stator iron (black). b) The active masses of the generators as function of the number of poles = 2p.

0.0115, if the superconductor is operated at $I/I_c = 80$ % and if a n-value of 20 is used. The cold loss will be $P_{SCloss} = 0.42$ W. A typical large cryocooler will need of the order 1-3 kW as input power to the compressor in order to provide a cooling power of 2-7 W at $T = 20$ K. Thus if such a unit is used then the cooling loss will be of the order 3 kW /11 kW = 0.27, which is much higher than the 1 % expected for a MW generator. The extensive cooling reserve will however allow a less optimal cryostat design due to the small size of the generator and the obtained reliability experience on the operation in a wind turbine environment can be utilized when a 10 times larger demonstrator should be build as the MW generator size is approached.

5. Conclusion

The possibility to install an IBAD coated conductor based direct drive generator in a 11 kW Gaia wind turbine has been investigated. Two race track coils have been wound and a degradation of the critical current was observed. The delamination of the tape due to thermally induced stresses are believed to be the course and will have to be controlled in order to utilize the potential of a large engineering current density of IBAD tape based coils. An analytical model was used to examine the active mass of generators fitting into the Gaia turbine and having an $J_e = 149$ A/mm^2. A 4 pole generator is suggested in order to obtain the cheapest small scale wind system consisting of superconducting field windings, a cryostat, a cryocooler, an aircore stator and a windturbine. The 4 pole machine will contain $m_s c = 11.8$ kg of coated conductor corresponding to $L_{SC} = 3.45$ km and the peak flux density of the generator will be $B_0 = 1.5$ T.

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