Design and analysis of air-core superconducting generator for wind power applications

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Abstract. In this paper, the design and analysis of the air-core superconducting (SC) generators are carried out. Air-core SC generators have the advantage of reducing the gross weight of the system because they do not have a high-weight iron core that constitutes a magnetic circuit, and can be a good design option with high power density. The magnetic field acting on the outside of the air-core SC generator can be shielded by using an active shielding SC coil. In this study, we compared the weight and output power of an air-core SC generator with an active shielding SC coil to that of conventional SC generators, and studied design conditions for application to wind power generation systems. The results show that the total weight of the generator with actively shielded SC generator has lower weight compare with conventional magnetically shielded SC generator.

1. Introduction

In the movement towards reducing CO₂ emissions and our dependence on fossil fuels, wind power is considered one of the main technologies in delivering renewable energy to the world. The European Wind Energy Association has predicted a need for 300 GW of installed wind power by 2030, with 120 GW of that expected offshore [1]. As of Jan 2016, there is 131 GW of onshore and 11 GW of offshore installed wind capacity in the EU [2]. This relatively low offshore capacity can be improved by higher power turbines, especially as wind turbine power ratings have been increasing in recent years with sizes on the order of 10-20 MW on the horizon. As wind turbine power needs increase further, generator technology must similarly improve to enable high-power wind generator development. One such technology is the inclusion of superconducting (SC) wire in generator designs to produce greater magnetic field strength with less material [3]. SC wind generator designs are typically direct drive, low speed, and high torque, and due to very high air-gap magnetic flux densities from the SC coils (3-5X compared to conventional designs) much of the flux-carrying steel within the machine can be eliminated, resulting in a more lightweight and compact turbine.

There are many feasibility and design studies with regard to SC generators for wind power applications. [4] and [5] presented 10 MW and 2 MW class SC wind turbine generators and demonstrated their finite element analysis (FEA) results and test methodologies. Their successful studies and experiments are shown the generator design and potential challenges of SC
generators for mega-watt scale wind power applications. [6] presented a feasible electromagnetic designs of SC generators for a 10 MW direct-drive wind turbine. The topology comparison of SC generators with more non-magnetic cores and with more iron core were described for low weight system.

With the introduction of a technology such as SC coils into wind generator design, new spaces open up for novel topologies and implementations. One such topology is the actively-shielded air-core SC machine described in previous work [7]. Originally designed for aircraft applications, this machine has not been analysed at larger scales such as wind generators. Furthermore, the potential for such a topology in offshore direct-drive applications has not yet been explored. In this paper, a first-pass at wind generator sizing is performed for the actively shielded air-core SC topology. The aim is to reduce the design weight for further optimization and to give some intuition as to the relative state of SC technology in potential wind generator applications.

2. Actively shielded air-core SC generator

2.1. Concept of actively shielded air-core SC machine

The actively-shielded air-core SC design is an inside-out synchronous machine, operating similar to a permanent magnet generator. SC dc field coils replace the permanent magnets, but they are held stationary in the outer portion of the machine to simplify the superconductor cooling scheme. The 3-phase copper armature coils are part of the rotating inner portion of the machine and are connected to an outside 3-phase system through slip rings. To reduce the magnetic field propagation outside the machine, active SC shielding coils are placed just beyond the dc field coils. The design of these coils has been optimized to minimize the outside magnetic field while maximizing the air-gap flux density within the machine; this tradeoff was achieved through a multi-objective electromagnetic optimization in prior work [8]. Figure 1 shows the main electrical components of the actively-shielded air-core machine. In figure 2, the architecture of actively shielded air-core superconducting machine model shows an example machine utilizing the air-core design with a cryocooler module, a torque tube formed around the SC coils, and slip rings for the rotating armature windings.

![Figure 1. Main electrical components of the actively-shielded air-core SC machine.](image1)

![Figure 2. Architecture of actively-shielded air-core SC machine.](image2)

2.2. Air-core SC generator for wind power applications

An reference SC wind power generator concept design was used as a starting point for sizing the air-core wind generators. In this reference design, low temperature superconducting magnets
were placed in the rotor, with copper windings around iron teeth in the stator [9]. Some key aspects in this reference design which are absent from the proposed air-core design include iron present in the stator, NbTi used as the SC wire material, and the SC coils placed in the rotor. In the air-core design there is very little flux-carrying iron in the machine, Nb$_3$Sn is used as the SC wire material, and the SC coils are held in the stator. It is expected that Nb$_3$Sn will allow for stronger magnetic flux density with less wire, and the lack of iron will drastically reduce the machines weight. The SC generator design constraints are listed in Table 1.

| Item                        | Value       |
|-----------------------------|-------------|
| Rated power (MW)            | 10          |
| Rated speed (rpm)           | 10          |
| Rated voltage (kV)          | 3.3         |
| Outer diameter (mm)         | 4800        |
| Armature copper depth (mm)  | 127         |
| Armature current density (A/mm$^2$) | 3.7       |
| Ampere-turns per pole (kAT/pole) | 906.4   |
| Pole count                  | 36          |

2.3. Sizing procedure for wind power applications
To allow for consistent comparisons between the reference and the air-core designs (with magnetic core and with active shielding SC coils), certain parameters were fixed during the sizing process. These include the rated speed, armature current density, and SC field coil amp-turns per pole as listed in Table 1. Additionally, the parameters of the SC coils were unchanged since the coils had been previously optimized to minimize outside magnetic field while maximizing air-gap flux density [7]. The diameter was limited below 4.8 m and the armature depth was limited below 127 mm (5 in), both based on the reference design [9]. These quantities were varied with the intent of minimizing the machines SC wire length, since SC wire is the most expensive component in the design, and SC wire is priced based on length and current-carrying capacity. Copper weight and SC wire weight were also examined since they contribute to material cost and overall machine weight. In offshore wind applications, the diameter of the generator module is not particularly restricted when compared to land based shipping limitations. For this reason, it is not uncommon to have diameters in excess of 4 m for offshore wind generators. Results were obtained through 2-D electromagnetic simulations of the generator cross section. For each value of diameter and armature depth, the active length needed for the desired power rating was calculated via simulation. Quantities for copper weight, SC weight, and SC wire length were then calculated based on the geometry of the machine and windings as well as known material properties. A fill factor of 0.5 was assumed for both copper and SC wires.

3. Design results and discussion
3.1. Flux density distribution
An 3D CAD model of a 10 MW class actively-shielded air-core SC generator for wind power application is shown in Fig. 3. The SC generator with magnetic shielding core (Air-core design 1) and the SC generator with actively-shielding coils (Air-core design 2) were designed to compare the performance and volume of the air-core type SC generator. As described above, the two-dimensional shape of the machine’s armature, physical airgap, and SC coils is the same, and the outermost diameter is fixed as 4.8 m.
Figure 3. 10MW class actively-shieldsed SC generator for wind power applications.

Figures 4 and 5 show the magnetic flux density distribution inside the SC generator with the magnetic shielding core. It can be seen that the magnetic shielding core and active shielding SC coils installed at the outermost part of the machine is properly shielding the high magnetic flux by the SC main field coil. In air-core design 1, Magnetic shielding core was applied with ferromagnetic stainless steel-SS400, and it was assumed that it had ideally one-piece shape.

Figure 4. Magnetic field distribution of magnetic core shielded SC generator.

Figure 5. Magnetic field distribution of actively-shielded SC generator.

Figure 6 shows the flux density distribution in the airgap of the designed air-core sc generators. In air-core design 1, the maximum value of airgap flux density is about 3.6T, and in air-core design 2 it is about 3.4T. It can be seen that the airgap flux density of the air-core design 2 is about 5% smaller in the identical 2D shape.

Figure 7 shows the flux density analysis results to confirm the magnetic flux shielding performance of the generators at the boundary of 5.8 m in diameter. The maximum radial...
flux density is about 0.007 T in the air-core design 1 and about 0.022 T in the air-core design 2. It can be seen that the magnetic flux shielding performance at the set boundary is about three times better in the air-core design 1 case.

3.2. Output characteristics and weight
As machine diameter increases, the amount of required copper and SC wire decreases. This decrease follows an inverse relation in accordance with the machine’s constant $D^2L$ factor; as the diameter increases, the active length must decrease exponentially to maintain the same power. Additionally, since the geometry of the SC coils was held constant, an increase in machine diameter requires an increase in the pole count. This adds to the SC wire weight and length, and becomes more pronounced for larger diameters as the pole count increases and the active length decreases. Increasing the armature depth allows for more torque-producing
material within the machine, which decreases the active length for a given diameter. In theory, there would come a point where the additional copper does not add significantly to the torque of the machine, and instead only increases the weight. This did not appear in the results, since that turning point is at a value beyond the current range.

Figures 8 and 9 show the output power vs. terminal voltage characteristics of two generators designed in this paper. Both generators have a terminal voltage of about 3.3-3.5 kV at the same operating point with an output of about 10 MW.

Table 2. Design parameters of reference and magnetic-core/actively-shielded 10MW SC generator.

| Item                     | Reference | Air-core design 1 | Air-core design 2 |
|--------------------------|-----------|-------------------|-------------------|
| Shield type              |           | Magnetic Core     | Active shielding  |
| Active length (m)        | 1.88      | 2                 | 2.2               |
| Rated current (A)        | 1750      | 1800              | 1800              |
| Armature current density (A/mm²) | 3.6       | 3.7               | 3.7               |
| SC coil material         | NbTi      | Nb₃Sn             | Nb₃Sn             |
| SC coil total length (km)| 720       | 800               | 1066              |
| SC coil total weight (kg)| 3840      | 4266              | 5685              |
| Armature copper weight (kg) | 9270   | 6000              | 6000              |
| Shield core weight (kg)  | -         | 45377             | 0                 |
| Total (ton)              | -         | 55.64             | 11.68             |

Figure 10. Comparison of weight for electrical components.

Design results are presented in Table 2 for a comparison of possible generators utilizing the air-core superconducting topology. Design parameters of reference and magnetic core shielding and actively-shielded SC generator are listed. As shown in the table, the magnetic core installed
for the shielding of the magnetic flux emitted to the outside in the air-core design 1 has a weight of about 45ton, which is more than 81.6% of the total electrical component weight in the generator. Figure 10 shows the comparison of weight for electrical components of magnetic core shielding and active shielding SC machines. This result also confirms that the total weight of the generator with the active shielding SC coil is about 21% of the generator weight with the magnetic shielding core when the two designed generators have the same output.

4. Conclusion
In this paper, 10MW class SC generator for offshore wind power application was designed and tested for its characteristics. The outside diameter of the SC generator was limited to 4.8 m by referenced design and an inside-out synchronous generator with a 3-phase armature rotating inside was designed. In the air-core design 2 with active shielding SC coils, the weight reduction effect of 79% or more was confirmed when comparing two devices having the same output. It is concluded that engineering trade-off studies are needed to reduce the cost by increasing the SC coil quantity and decreasing the weight of the whole machine.

In the immediate future, more constraints will be added to the optimization study. These include the weight of support structures, the cost of SC wire, and the addition of cooling for the SC wires. Additionally, optimization of the SC coil geometry would expand the design space by decoupling the pole count from the diameter. An analysis of thermal limits within the machine would also prove useful, as it could potentially allow for higher current densities within the armature and shorter active lengths. A more exhaustive multi-objective approach is the most reasonable next step to implement these improvements.

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