High Temperature Superconducting Halbach Array Topology for Air-cored Electrical Machines

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Abstract. Air-cored electrical machines have attracted increasing attention in applications related to aircraft and wind power because they can eliminate core losses and decrease the total mass. However, the limited magnetic flux in air-cored machines has restricted their power level. In order to improve the power density and efficiency while further reducing the weight of air-cored electrical machines, a novel field winding topology composed of high temperature superconducting (HTS) Halbach Array magnets (HAM) has been proposed in this paper. C-GEN is an innovative multi-stage air-cored generator technology with permanent magnets, which has been demonstrated at laboratory scale. Taking a 1 MW C-GEN generator prototype as the example machine, an \textbf{H}-formulation founded HTSHAM model has been built in COMSOL Multiphysics with the homogenization method. Simulation results show that the proposed HTSHAM C-GEN generator can achieve a power density more than 4 times higher than the conventional design with permanent magnets (PM), with a reduced magnet weight of around half of the previous prototype. The proposed HTSHAM represents a generic approach for the design of fully air-cored superconducting synchronous machines, eliminating heavy ferromagnetic material, and thus provides a useful reference for the design of low-weight air-cored electrical machines with a high power density.

1. Introduction
Air-cored electrical machines have prompted widespread interests in multiple domains such as aircraft [1], flywheel energy storage systems [2], as well as wind turbines [3]-[4], in that they constitute magnetic circuits without heavy ferromagnetic material and, thus, can not only reduce the total weight but also get rid of core losses [5]. C-GEN is a multi-stage air-cored permanent magnet (PM) generator technology developed at the University of Edinburgh, which can be used for wind, tidal and wave energy converters [6]-[7]. A C-GEN generator is composed of a number of stator and rotor modules. Each stator module includes several copper coils, which are mounted onto the stator blade. A single rotor module comprises C-cores with magnets mounted in the inside surface, which produces an axial magnetic flux. As clean and renewable energy, wind power has aroused increasing attention and the wind turbine market has been growing rapidly. C-GEN wind turbines have been designed for improving wind power utilization efficiency, which have many advantages, such as no cogging torque, high degree of modularity, low capital expenditures, etc. [4]-[7]. However, they still have some drawbacks to be overcome, such as low capacity, large size, and heavy weight.

Superconducting technology has long been pursued in industries, especially regarding electric machines, because of its outstanding advantages of higher power density and current carrying capacity, etc. over conventional methods [8]-[16]. The emergence of high temperature superconductors (HTS), which can operate in liquid nitrogen, has made the large-scale offshore application possible. The approximately zero DC resistance of HTS material can effectively increase the power generation
efficiency of wind turbines. Additionally, superconducting wind turbines possess some distinctive advantages, e.g. low synchronous impedance, low noise, low harmonic content, simple maintenance and so on [17]-[18].

A conventional Halbach Array is composed of PMs that can concentrate the magnetic flux on one side of the array and cancel it on the other side [19]. It is usually applied in linear machines to improve their power efficiency by condensing the magnetic flux density exposed to coils [20]-[22]. However, it is hard for the conventional Halbach Array to achieve an intensity higher than 1 T. Therefore, the concept of a superconducting Halbach Array magnet (HAM) has been proposed for MRI scanners [23]-[24].

On the basis of the above research, to further improve the performance air-cored electrical machines, taking a C-GEN wind turbine prototype as the studied example machine, a novel field winding topology composed of HTHAM has been put forward in this paper. Firstly, founded on a 4-stage 1 MW PM C-GEN prototype, a 2D model of the generator module has been built in COMSOL Multiphysics and its magnetic field distribution has been simulated. Then, the PMs used in the studied module has been replaced with HTHAMs, of which the modelling has been conducted based on H-formulation with a homogenization method [25]-[26]. Through comparison with the PM C-GEN prototype, results show that the application of HTHAMs can not only generate an average magnetic flux density over 4 times of the former in the stator region but also reduce the magnet weight to around one half. Therefore, the torque density and power level of the generator can be well improved.

This work provides a useful reference for the future design of fully air-cored synchronous machines, and the results can be used to guide the manufacture and application of HTS Halbach Arrays.

2. Shear stress
C-GEN wind turbines work by producing shear stress in the air-gap. Here, we can define the average air-gap shear stress of the whole generator modules, noted as $\tau$, as

$$
\tau = \frac{T}{Sl} = \frac{T}{\pi \cdot (r_e^2 - r_i^2) \cdot l} \tag{1}
$$

where $T$ is the total developed torque, $S$ is the effective action area of the shear stress, decided by the outer radius $r_e$ and inner radius $r_i$ of the copper coils, and $l$ represents the length of the air-gap.

As both the flux density $B(\theta)$ and the stator surface current density $K(\theta)$ for the copper coils are sinusoidal flux waves, then we have

$$
\tau = \frac{1}{2 \pi} \int_0^{2 \pi} K \cdot B d\theta = \frac{K_{\text{max}} B_{\text{max}}}{2} \tag{2}
$$

where $K_{\text{max}}$ and $B_{\text{max}}$ are respectively the amplitude of the current density and magnetic flux density. Then, the power density transferred by the rotor movement can be obtained as

$$
P = \frac{T \cdot \omega}{Sl} = \frac{\tau \cdot \omega}{Sl} = \frac{K_{\text{max}} B_{\text{max}} \cdot \omega}{2} \tag{3}
$$

where $\omega$ is the angular velocity.

From (1)-(3), it can be seen that the average shear stress represents the torque density in the stator region of the C-GEN wind turbine. The augment of magnetic flux density can increase directly the torque density then improve the power density. Therefore, magnetic flux density is the key parameter to be studied in this paper.

3. Modelling of PM C-GEN generator module
The diagram of a PM C-GEN generator is shown in Figure 1. It can be seen that the whole generator is composed of multiple detachable C-core modules, and each module contains several couples of PMs (rotor) and copper coils (stator). The magnetic flux is established by PMs, which passes through the copper coils. All the parameters of the 1MW PM C-GEN generator can be found in Table 1.

According to the parameters presented in Table 1, a 2D model of the PM C-GEN generator module has been established in COMSOL Multiphysics, as shown in Figure 2. This modelling is based on the
middle cross-section of the generator module. The dark green parts represent the generator shell made of stainless steel, the orange parts represent the copper coils, and the grey parts are PMs. The used PM is of type-NdFeB Grade N42, and its residual magnetism is 1.28 T.

![Diagram of the PM C-GEN design. (a) Whole body. (b) C-core module cross-section.](image)

**Figure 1.** Diagram of the PM C-GEN design. (a) Whole body. (b) C-core module cross-section.

| Parameter   | Quantity          | Value          |
|-------------|-------------------|----------------|
| \( R_i \)   | inner radius      | 2655 mm        |
| \( R_o \)   | outer radius      | 3190 mm        |
| \( L \)     | magnet length     | 312 mm         |
| \( w_m \)   | magnet average width | 78 mm   |
| \( t_m \)   | magnet thickness  | 15 mm          |
| \( \rho_{mm} \) | magnet mass density | 7.7 g/cm\(^3\) |
| \( B_r \)   | residual magnetism | 1.28 T        |
| \( l \)     | air-gap between magnets | 34 mm |
| \( d_a \)   | adjacent magnet distance | 21 mm |
| \( t_c \)   | copper coil width | 22 mm          |

**Table 1.** Parameter specification for the C-GEN prototype.

The simulated magnetic field distribution is shown in Figure 3 (the copper coils have been hidden for a better view). It can be found that the highest flux density appears in the part of the stainless steel shell, which is due to its high permeability. To figure out the properties of the magnetic flux that passes through copper coils, a rectangular region between permanent magnets has been especially studied, as marked in white in Figure 3. The magnetic flux density distribution of this area has been presented in Figure 4, which exhibits an approximate saddle face. It can be found that the highest flux density attains around 0.6 T, but it is concentrated in the region adjacent to the magnets of the module middle position, where two magnets are put together closely in parallel. The lowest flux density, around 0.5 T, appears at both ends of the stator region along the \( x \)-axis. In general, the average flux density, \( B_{avg} \), in the stator region is approximately 0.56 T.


Figure 2. Modelling of the C-GEN generator module in COMSOL Multiphysics.

Figure 3. Magnetic field distribution inside the 1 MW C-GEN generator module.

Figure 4. Flux density distribution in the stator area between PMs. Average flux density $B_{\text{avg}} = 0.56$ T.
As far as the weight of each permanent magnet is concerned, it should be equal to \( \rho \times t \times w_a \times L \approx 2.81 \text{ kg} \). For the 4-stage 1 MW C-GEN wind turbine, there are totally 22 modules and 32 pieces of magnets in each module, thus the total weight of the magnets is around 1980 kg.

4. Modelling of HTSHAM

In the new design for the HTS C-GEN generator, HTSHAMs have been used to replace PMs to obtain a higher magnetic field flux density, as shown in Figure 5. The two groups of golden coils are HTSHAMs, and the borrow coils represent the copper coils. The basic idea of the HTSHAM is to create a continuous magnetic channel with a group of HTS coils carrying DC.

![Figure 5. Diagram of the coil parts of the HTSHAM C-GEN module.](image)

As mentioned in [27], with the no-insulation (NI) winding technique, the absence of both turn-to-turn insulation and the extra stabilizer can make the NI HTS magnet highly compact and enhance its overall current density. Therefore, in this paper, the HTSHAM model was constructed with NI technique on the basis of stabilizer-free HTS coated conductors (CCs) manufactured by SuperPower, Inc., SF12050 [23]-[24]. It is composed of a 1-\( \mu \)m thin film of YBCO material, and all its parameters used for modelling are shown in Table 2.

| Symbol   | Quantity                  | Value          |
|----------|---------------------------|----------------|
| \( w \)  | HTS CC width              | 12 mm          |
| \( h_{HTS} \) | YBCO film thickness  | 1 \( \mu \)m   |
| \( t \)  | HTS CC thickness         | 0.055 mm       |
| \( T \)  | operation temperature    | 77 K           |
| \( I_{c0} \) | critical current in self field | 300 A         |
| \( n \)  | \( n \)-value             | 21             |
| \( I \)  | applied current           | 225 A          |
| \( B_0 \) | magnetic field constant   | 0.426 T        |
| \( \rho_m \) | mass density              | 8.96 g/cm\(^3\) |
| \( E_0 \) | characteristic E-field    | \( 10^{-4} \) V/m |
| \( \mu_0 \) | Free space permeability   | \( 4\pi \times 10^{-7} \) H/m |
4.1 Modelling principle
According to Maxwell’s equations, we have
\[ \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \]  
\[ \nabla \times \mathbf{H} = \mathbf{J} \]  
where \( \mathbf{E} \) is the electric field, \( \mathbf{B} \) is the magnetic flux density, \( \mathbf{H} \) represents the magnetic field intensity, and \( \mathbf{J} \) signifies the current density.

From Constitutive Law, it is obtained that
\[ \mathbf{B} = \mu_0 \mu_r \mathbf{H} \]  
where \( \mu_0 \) is the free space permeability, and \( \mu_r \) is the relative permeability of the studied material.

According to Ohm’s Law, we have
\[ \mathbf{J} = \sigma \mathbf{E} \]  
where \( \sigma \) is the conductivity of the material.

On the basis of (4), (5), (6) and (7), the general form of \( \mathbf{H} \)-formulation can be obtained as
\[ \nabla \times \left( \nabla \times \mathbf{H} \right) + \mu_0 \mu_r \frac{\partial \mathbf{H}}{\partial t} = 0 \]  
To solve (8) in COMSOL Multiphysics, the material properties of the HTS CC have to be defined. According to the \( \mathbf{E} \)-\( \mathbf{J} \) power law [30]
\[ J_c \mathbf{E} = J_c \mathbf{E}^n \]  
we obtain
\[ \sigma = \frac{J_c}{E_0} \left( \frac{J_c}{E_0} \right)^{n-1} \]  
where \( J_c \) is the critical current of the HTS CC, with [26]
\[ J_c = \frac{J_{c0}}{1 + \sqrt{\frac{k^2 |B_\parallel|^2 + |B_\perp|^2}{B_0}}}^{\alpha} \]  
where \( J_{c0} \) is the critical current in self-field, \( \mathbf{B}_i \) is the local magnetic flux density parallel to the surface of the HTS tape, and \( \mathbf{B}_\perp \) is the corresponding perpendicular component. \( B_0 \) is a constant determined by the HTS material, \( k = 0.186 \), and \( \alpha = 0.7 \) [23]-[24].

According to all the above equations, we can obtain the specific \( \mathbf{H} \)-formulation for the HTSHAM modelling, as
\[ \frac{E_0}{J_{c0}} \left( 1 + \mu_0 \mu_r \sqrt{\frac{k^2 |\mathbf{H}_\parallel|^2 + |\mathbf{H}_\perp|^2}{B_0}} \right)^{2n} \cdot \nabla \times \mathbf{H}^{n-1} \cdot \nabla \times \left( \nabla \times \mathbf{H} \right) + \mu_0 \mu_r \frac{\partial \mathbf{H}}{\partial t} = 0 \]  
where \( \mathbf{H}_\parallel \) and \( \mathbf{H}_\perp \) are respectively the parallel and perpendicular components of the local magnetic field.

4.2 Homogenization method
Considering that each HTSHAM coil is composed of many HTS CCs, and each HTS CC contains several typical layers (namely silver layers, one substrate layer, and one HTS layer), it can be quite computationally intensive and time-consuming to build a comprehensive model for the HTSHAM. Therefore, to simplify the modelling and save computation time, a homogeneous model for the HTSHAM has been proposed here, based on the homogenization method mentioned in [25]-[26]. In this model, a single HTS CC has been presented as a unit cell composed of all the 4 layers, and only the
supercritical material’s volume fraction has been taken into account, as shown in Figure 6.

![Diagram of the homogenization equivalence.](image)

**Figure 6.** Diagram of the homogenization equivalence.

Thus, for the homogeneous HTS CC, the equivalent critical current density \( J_{c,\text{eq}} \) can be expressed as

\[
J_{c,\text{eq}} = J_c \cdot f_{\text{HTS}} = \frac{J_c \alpha}{1 + \sqrt{\frac{k^2 \| B_1 \|^2 + \| B_2 \|^2}{B_0}}} \cdot f_{\text{HTS}}
\]

where \( f_{\text{HTS}} \) is the volume fraction of YBCO per unit cell, with [25]

\[
f_{\text{HTS}} = \frac{h_{\text{HTS}}}{t}
\]

where \( h_{\text{HTS}} \) is the thickness of the YBCO thin film, and \( t \) represents the whole thickness of the CC.

It should be noted here that a new pointwise constraint has to be defined in this model to assure the applied current. In other words, the transport current has to be guaranteed to be equal to the integral of current density over the coil cross-section. Therefore, we have [26]

\[
I_i - \int A J(x, y) dA = 0
\]

where \( A \) is the cross-sectional area of the studied HTS coil.

5. Results and analysis

A 2D model for the HTSHAM has been built in COMSOL Multiphysics, as shown in Figure 7.

![Diagram of the HTSHAM modelling in COMSOL Multiphysics.](image)

**Figure 7.** Diagram of the HTSHAM modelling in COMSOL Multiphysics.
Compared with Figure 2, all the PMs have been replaced by HTS coils, which form two groups of HTSHAMs. The basic principle is not to change the whole dimension of the generator module along the $x$-axis and the air-gap between the rotor and the stator.

5.1 Preliminary design
The air-gap between HTS coils along the $x$-axis is set as 30 mm, and each coil is composed of 300 turns of HTS tapes. The simulated results are shown in Figure 8. It can be found that a closed magnetic field loop has been established in each HTSHAM, and almost all the magnetic fields are confined inside the HTSHAM. The highest flux density attains 3.85 T, which appears onto the inner parts of the coils in the Halbach area, so the cryogenic condition here ought to be well guaranteed especially. It should be pointed out that, the magnetic flux is parallel to the surface of the HTS tapes, but the critical current of the coils is mostly influenced by the perpendicular components of the field, of which the peak amplitude (approximately 0.3 T) is less than $B_0$. Therefore, a current-carrying rate of no more than 75% is acceptable for this HSTHAM design.

![Figure 8. Magnetic field distribution inside the HTSHAM C-GEN generator module.](image)

![Figure 9. Flux density distribution in the stator area between HTS coils. $B_{avg} = 1.91$ T.](image)
To study the magnetic flux density in the stator region, their distribution in the white rectangular region (same size as before) of Figure 8 has been shown in Figure 9. It can be seen that the flux density in this area also exhibits an approximate saddle face, with the highest value attaining 2.59 T in the area next to the HTS coils. Through calculation, the average flux density of this studied region is 1.91 T, which is about 3.4 times that of the PM design.

The cross-sectional area of each HTS coil is 16.5 mm×12 mm = 198 mm², and the average length of the coil is π×46.5 mm×312 mm×2 ≈ 770 mm. Considering that the 4-stage HTSHAM C-GEN contains 32×22 superconducting coils, thus the total weight of the magnets should be ρm×198 mm²×770 mm×32×22 ≈ 961.4 kg < 1980 kg. Therefore, the design with HTSHAMs can decrease the total magnet weight to less than half of the PM C-GEN.

5.2 Design Optimisation

In order to further increase the flux density in the stator area, the air-gap between two groups of HTSHAMs has been reduced and the number of HTS tapes in each coil has been increased accordingly. When the air-gap decreases from 30 mm to 20 mm and the number of tapes increases from 300 to 330, the average flux density in the same studied region attains 2.11 T; while the air-gap drops to 10 mm, and the turn number augments to 360, the average flux density reaches 2.31 T.

Figure 10 and Figure 11 show respectively the magnetic field and flux density distribution for the 10 mm-air-gap case. In this case, the cross-sectional area of the HTS coil is 19.8 mm×12 mm, and its average length is π×58.85 mm×312 mm×2. Therefore, the total HAM weight amounts to 1212.2 kg, which accounts for about 60% of the magnet weight in the PM design.

![Figure 10. Magnetic field distribution inside the optimised HTSHAM C-GEN generator module.](image-url)
To more comprehensively compare the HTSHAM designs with the conventional PM C-GEN, their power levels and magnet weight have been summarized in table 3.

| C-GEN design       | PM   | HTSHAM 1 | HTSHAM 2 | HTSHAM 3 |
|--------------------|------|----------|----------|----------|
| Air-gap along x-axis (mm) | 30   | 30       | 20       | 10       |
| Number of CCs in a coil | /    | 300      | 330      | 360      |
| Power level (MW) | 1    | 3.41     | 3.77     | 4.13     |
| Magnet weight (kg) | 1980 | 961.4    | 1096.8   | 1212.2   |

6. Conclusions
This paper has proposed a novel HTS Halbach Array topology for air-cored electric machines. The average shear stress represents the torque density of synchronous machines, which is in a positive correlation to the magnetic field distribution in the stator region. Therefore, the magnetic flux density has been specially studied in this paper. Both the 1 MW PM C-GEN generator prototype and the new HTSHAM design have been modelled and analysed in COMSOL Multiphysics. The application of HTSHAMs can increase the average magnetic flux density from 0.56 T to 2.31 T in the stator region without changing key dimensions. In other words, the power level of the proposed HTSHAM C-GEN generator can attain approximately 4.13 MW. Besides, the total magnet weight of the HTSHAM C-GEN generator can be reduced to approximately 60% compared with the conventional PM design.

To conclude, this paper puts forward a novel application of superconducting Halbach Arrays to synchronous machines. The proposed HTSHAM can not only generate a higher power density and decrease the magnet weight for the example C-GEN machine in the paper, but also represents a generic topology/approach for the design of fully air-cored superconducting machines, eliminating heavy iron cores. This paper is believed to be a useful reference for the future development of low-weight air-cored electrical machines with a high power density.

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