Investigation on Effect of Shape of HTS Pole Coil on Airgap Magnetic Field of HTS Synchronous Motor

D K Sharma¹², V A S Muralidhar Bathula², A S Gour¹, V V Rao¹

¹ Indian Institute of Technology, Kharagpur, India
² BHEL Corporate R&D Division, Hyderabad, India

Email: devsharm@gmail.com

Abstract. The High Temperature Superconducting (HTS) synchronous motors offer considerably higher torque and power densities along with higher efficiencies for strategic and critical industrial applications. The most widely explored airgap based topology for HTS synchronous motors has conventional copper windings in stator and HTS pole coils in the rotor. The shape of these rotor pole coils affects various electrical parameters of the motor. In this paper, a detailed investigation has been carried out on effect of shape of HTS pole coil on airgap magnetic field and rated open circuit characteristic (OCC) of an 8 MW HTS synchronous motor along with its other parameters like pole coil excitation current, peak magnetic field inside the motor, maximum perpendicular magnetic field on HTS tape and operating temperature of HTS pole coils through FEM based electromagnetic analysis. Based on the results of electromagnetic analysis, the optimum shape of HTS pole coil has been finalised.

1. Introduction
The High Temperature Superconducting (HTS) synchronous motors have become popular choice for various strategic and critical industrial applications where high torque and power densities are essentially required along with higher efficiencies at all operating loads conditions [1,2]. Among various available topologies for HTS synchronous motors, the most widely explored one is airgap based topology which has conventional copper-based windings in stator and HTS based pole coils in rotor [3,4]. Figure 1 shows the schematic of a typical airgap topology based HTS synchronous motor. On stator side, it has conventional copper-based windings placed in a non-magnetic core supported on a cylindrical magnetic shield made of ferromagnetic material. On rotor side, it has HTS pole coils kept under cryogenic environment. The HTS rotor also has other essential sub-components like torque tubes, thermal radiation shield, vacuum sleeve, rotary coupling etc. as shown in figure 1.

One of the most essential and costliest components of a HTS rotor is the pole coil. Usually, the HTS pole coils are made in racetrack shape and are realized by a stacking few identical double pancake coils one over the other. The design and shape of these HTS pole coils play a very crucial role in determining the airgap magnetic field [5,6]. The airgap magnetic field is one of the most essential electrical parameters for determining the rated open circuit voltage [7]. The rated Open Circuit Characteristic (OCC) is a condition where the rotor spins at synchronous speed with rated DC excitation in pole coils and the voltage observed in the open circuited stator winding is equal to the rated voltage of the motor. In the present paper, the rated OCC condition for 8 MW HTS motor is studied for various design cases of HTS pole coils.
2. Specifications of HTS Synchronous Motor and Pole Coil

In the present paper, a three phase, 8 MW, 500 RPM HTS synchronous motor having airgap based topology is considered. The broad technical specifications of the HTS synchronous motor are given in table 1 below. The HTS synchronous motor under consideration has a three phase, star connected conventional copper-based stator winding, whereas, the rotor has HTS pole coils. The airgap magnetic field of this HTS synchronous motor is studied for four HTS pole coil variants generated by changing the pole shoe gap i.e. the gap between the two rectilinear portions of the coil.

Table 1. Technical Specifications of HTS Synchronous Motor.

| S. No. | Parameter                | Value  |
|--------|--------------------------|--------|
| 1      | Power Output             | 8 MW   |
| 2      | Voltage (Line-to-Line)   | 6600 V |
| 3      | Frequency                | 50 Hz  |
| 4      | RPM                      | 500 RPM|
| 5      | No of Poles              | 12 Poles|

The 8 MW HTS synchronous motor under consideration has 12 HTS pole coils in the rotor as shown in figure 2. Each single HTS pole coil in the figure is obtained by stacking five identical racetrack shaped double pancake coils having equal number of turns of HTS tape.

The shape of this HTS pole coil plays a significant role in determining the airgap magnetic field of HTS motor along with other parameters like pole coil excitation current, peak magnetic field inside the motor, maximum perpendicular magnetic field on HTS tape and operating temperature of HTS pole coils. The airgap magnetic field is one of the essential electrical design parameters which determines the rated OCC voltage of the motor for a given of HTS synchronous motor. In an HTS synchronous motor, the airgap magnetic field is created by HTS pole coils which are made of HTS tape. In the present work, the YBCO based 2G HTS tape is chosen. The technical specifications of HTS tape are given in table 2 below.
Figure 2. HTS rotor having 12 pole coils.

Table 2. Technical Specifications of HTS tape.

| S. No. | Parameter                  | Value                      |
|--------|----------------------------|----------------------------|
| 1      | Make                       | SuperPower                 |
| 2      | Type of HTS tape           | YBCO (SCS4050-i-AP)        |
| 3      | Critical Current ($I_c$)   | $130 \, \text{A} \, @ \, 77 \, \text{K}, \, \text{sf}$ |
| 4      | Average thickness of HTS tape | 0.161 mm                   |
| 5      | Average width of HTS tape  | 4.05 mm                    |
| 6      | HTS tape Insulation        | Polyimide                  |
| 7      | Stabilizer                 | Copper                     |
| 8      | Critical bending diameter  | 11 mm                      |
| 9      | Critical tensile strength  | 550 MPa                    |

In general, the current carrying capacity of HTS tape selected for HTS synchronous motor is determined based on perpendicular magnetic field on it and its operating temperature. The critical current ($I_c$) of chosen 2G HTS tape at various perpendicular magnetic fields ($B_\perp$) for different operating temperatures are provided by manufacturer and given in figure 3 below [8].

Figure 3. $I_c$ vs $B_\perp$ characteristic of HTS tape at various operating temperatures [8].
3. Electromagnetic Analysis of various Design Variants of HTS Pole Coil

In this section, the details of electromagnetic analysis carried out for different design variants of HTS pole coil of the motor are presented. The electromagnetic analysis of 8 MW HTS synchronous motor (whose specifications are given in table 1) is carried out in ANSYS® Maxwell software for four design variants of HTS pole coil.

Figure 4 (a) and 4 (b) show the isometric view and sectional view of single HTS pole coil respectively. Figure 4 (c) shows the two-dimensional model of HTS pole coil. As shown in figure 2, the rotor of the motor has 12 HTS pole coils. Hence, during modeling of motor, 12 such pole coils have been modeled. The height of HTS pole coil and the overall width of HTS tapes within a pole coil are considered as constant during electromagnetic analysis. The gap ‘g’ between two rectilinear portions of pole coil is termed as pole shoe width as shown in figure 4 (a) and 4 (c).

![Figure 4. (a) Isometric view, (b) sectional view and (c) 2D model of HTS pole coil.](image)

Figure 5 shows the model of 8 MW HTS synchronous motor prepared in ANSYS® Maxwell software. The conductors of all three phases (R, Y and B phases) of the stator winding along with magnetic shield are modeled. The HTS rotor is also modeled with 12 numbers of HTS pole coils.

![Figure 5. Model of 8 MW HTS synchronous motor developed in ANSYS® Maxwell software.](image)
Various electromagnetic simulations are carried out to study the effect of variations of pole shoe width \( g \) between two rectilinear portions of HTS pole coil on airgap magnetic field. Table 3 shows four design variants having different shapes of HTS pole coil created by varying pole shoe width \( g \) from 40 mm to 100 mm in four regular intervals.

**Table 3. Design variants of HTS pole coil.**

| Design variant | Case A | Case B | Case C | Case D |
|----------------|--------|--------|--------|--------|
| Pole shoe width \( g \) | \( g=40 \) mm | \( g=60 \) mm | \( g=80 \) mm | \( g=100 \) mm |

For all four cases, the HTS pole coil excitation \( I_f \) is varied to obtain the rated OCC condition \( (E_l=6600 \text{ V}) \) and their magnetic field plots. Figure 6 shows a typical zoomed-in-view of magnetic field plot (B-plot) of HTS motor under rated OCC condition depicting the locations of the radial airgap magnetic field \( (B_g) \), the peak magnetic field \( (B_{\text{peak}}) \) and the maximum perpendicular magnetic field on HTS tape \( (B_{\bot\text{max}}) \).

![Figure 6. Location of \( B_{\text{peak}}, B_g \) and \( B_{\bot\text{max}} \) in the B-Plot of Case D.](image)

The effect of shape of the HTS pole coil for all these four cases at rated OCC condition on airgap magnetic field \( (B_g) \), the rotor excitation current \( (I_f) \), the peak magnetic field inside the motor \( (B_{\text{peak}}) \) and maximum perpendicular magnetic field on HTS tape \( (B_{\bot\text{max}}) \) are evaluated and presented in next section.

4. Results and Discussions

The rated OCC conditions are simulated for all four cases (as given in table 3). Figure 7 shows the zoomed-in-view of magnetic field plot (B-Plot) for all four cases. It can be seen from B-Plot that the radial airgap magnetic field \( (B_g) \) is nearly constant for all four cases. The peak magnetic field \( (B_{\text{peak}}) \) for Case A \( (g=40 \) mm) is higher. However, as pole shoe width \( g \) is increased from 40 mm to 100 mm, this peak magnetic field \( (B_{\text{peak}}) \) reduces.
Figure 7. Magnetic field plot for all four cases.

Table 4 below shows the rotor excitation current ($I_f$), the peak magnetic field inside the motor ($B_{\text{peak}}$), the radial airgap magnetic field ($B_g$) and maximum perpendicular magnetic field on HTS tape ($B_{\perp\text{max}}$) for rated OCC condition for all four cases. It can be observed from the table 4 that as the pole shoe width ‘$g$’ increases from 40 mm to 100 mm, the excitation current ($I_f$) as well as the maximum perpendicular magnetic field ($B_{\perp\text{max}}$) on HTS tape decreases. It can be ascertained that when the pole shoe width ‘$g$’ is the largest (as in Case D with $g=100$ mm), the excitation current ($I_f$), the peak magnetic field ($B_{\text{peak}}$) and the maximum perpendicular magnetic field ($B_{\perp\text{max}}$) are lesser as compared to that for other three cases.

Table 4. $I_f$, $B_{\text{peak}}$, $B_g$ and $B_{\perp\text{max}}$ for all four cases at rated OCC condition.

|       | $I_f$   | $B_{\text{peak}}$ | $B_g$  | $B_{\perp\text{max}}$ |
|-------|---------|-------------------|--------|------------------------|
| Case A ($g=40$ mm) | 346.1 A | 11.27 T           | 1.28 T | 6.02 T |
| Case B ($g=60$ mm) | 282.5 A | 8.87 T            | 1.26 T | 5.01 T |
| Case C ($g=80$ mm) | 240.7 A | 7.32 T            | 1.24 T | 4.49 T |
| Case D ($g=100$ mm) | 211.4 A | 6.40 T            | 1.22 T | 4.18 T |

Further, considering the data given in table 4, the operating temperature of pole coil with chosen HTS tape (whose specifications are given in table 2) is estimated considering a suitable margin-of-safety (in our case 67%) above operating current for all four cases. For example, the excitation current ($I_f$) for Case A (for $g=40$ mm) is 346.1 A and, with margin-of-safety, the operating excitation current is 578 A. The operating point (6.02 T, 578 A) for Case A is highlighted on $I_c$ vs $B^\perp$ characteristic of HTS tape. Similarly, the operating points for other three cases are also evaluated and highlighted in figure 8. Based on the operating point of Case A, it can be observed from figure 8 that the next nearby temperature at which this HTS pole coil (for $g=40$ mm) can possibly be operated is 4.2 K. Similarly, the possible nearby operating temperatures for other three cases are also arrived at. The maximum perpendicular magnetic field ($B_{\perp\text{max}}$) on HTS tape, the evaluated operating current with safety margin and nearby operating temperature for all four cases are presented in table 5.
Figure 8. Operating points for all four cases on $I_c$ vs $B_{\perp}$ characteristic of HTS tape.

| Case       | $B_{\perp}\text{max}$ | Operating current with safety margin | Nearby operating temperature |
|------------|------------------------|-------------------------------------|-------------------------------|
| Case A ($g=40$ mm) | $6.02\ T$              | $578\ A$                           | $4.2\ K$                     |
| Case B ($g=60$ mm) | $5.01\ T$              | $472\ A$                           | $10\ K$                      |
| Case C ($g=80$ mm) | $4.49\ T$              | $402\ A$                           | $20\ K$                      |
| Case D ($g=100$ mm) | $4.18\ T$              | $353\ A$                           | $30\ K$                      |

5. Conclusions

An 8 MW HTS synchronous motor is simulated at rated OCC condition for four different HTS pole coil shapes with varying pole shoe width in ANSYS® Maxwell software. Various electrical and magnetic parameters at rated OCC condition are obtained and compared for all four cases. The results of electromagnetic analyses suggest that, among all four cases, Case D ($g=100$ mm) gives the least operating excitation current at a reasonably good operating temperature of $30\ K$. Also, among all four cases, Case D gives the least perpendicular magnetic field on HTS pole coil and the least maximum magnetic field in the HTS synchronous motor.

6. References

[1] S S Kalsi 2004 IEEE Power Engineering Society General Meeting 2 2047-2048 (Denver, CO, USA)
[2] Michael Frank et al. 2006 IEEE Transactions on Applied Superconductivity 16(2) 1465-1468
[3] G Klaus, M Wilke, J Fraunhofer, W Nick and H W Neumuller 2007 IEEE Power Engineering Society General Meeting 1-8 (Tampa, FL, USA)
[4] Naoki Maki, Mitsuru Izumi, Masayoshi Numano, Kiyoshi Aizawa, Kagao Okumura and Katsunori Iwata 2007 International Conference on Electrical Machines and Systems (ICEMS) 1523-1527 (Seoul, South Korea)
[5] Y Jiang, R Pei, W Xian, Zhibin Hong and Timothy Coombs 2007 Superconductor Science and Technology 20(7) 585-591
Acknowledgments
Authors would like to extend their warm gratitude to the management of BHEL Corporate R&D Division, Hyderabad for giving an opportunity and extending full support to carry out this work.