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Electromagnetic analysis of 0.2 MW High Temperature Superconducting (HTS) synchronous machine for HTS pole coils development

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Abstract. High Temperature Superconducting (HTS) synchronous machine consisting of six HTS poles in the rotor and air gap copper windings in the stator will help in manufacturing compact, lightweight, high power density, high over load capacity and low noise machines for ship propulsion applications. In this paper electromagnetic simulation of pole coils for 0.2 MW HTS synchronous machine is discussed. This involves FEM based electromagnetic simulation of 0.2 MW synchronous machine with air gap configuration of copper stator winding and HTS rotor. The primary focus of the paper is to calculate magnetic field along parallel and perpendicular directions to HTS tapes in six pole rotor configuration. These results are required for selection of HTS to develop superconducting pole coils for manufacturing prototype HTS synchronous machine. In this process, air gap flux density and voltage generated in the machine are also calculated.

1. Introduction

The industrial scale production of high current density High Temperature Superconducting(HTS) tapes is encouraging the development of High Temperature Superconducting synchronous machines for industrial and ship propulsion applications [1], [2]. The topology of air gap copper winding in stator and HTS field coil winding in rotor will help in manufacturing compact, lightweight, high power density, high over load capacity and low noise machines for ship propulsion applications [3]. The schematic of such typical HTS synchronous machine (generated in CAD) is shown in Figure. 1.

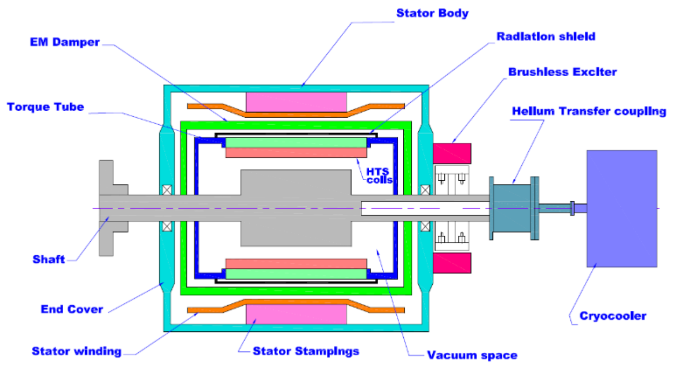

Figure 1. Schematic of HTS synchronous machine modelled using CAD

The present paper discusses electromagnetic analysis of a 0.2 MW HTS machine. This FEM based electromagnetic analysis was carried out based on the output of analytical design programme to finalise Ampere Turns (AT) of pole coil satisfying the required open circuit voltages in both analytical and FEM based electromagnetic simulation. In this electromagnetic analysis the open circuit voltage is estimated and compared with analytical design voltage to confirm the Ampere Turns (2,25,500) requirement of the HTS pole coil. After the verification of AT requirement in pole coil through open circuit characteristics, the parallel and perpendicular magnetic fields were estimated for selection of HTS tape for development of HTS pole coil of synchronous machine.

2. HTS Synchronous Machine Parameters

A computer aided program was developed for design of 0.2 MW HTS synchronous machine. The specifications of HTS synchronous machine considered for electromagnetic analysis are listed in Table 1.

Table 1. Rating of the HTS synchronous machine

S.No.	Parameters	Values
1	Rating of the machine	200 kVA
2	Voltage (Phase)	239.6 V
3	No of phases	3 Phase
4	Speed	250 RPM
5	No of pole pairs	3
6	Power factor	Unity
7	Stator winding type	Star connected

3. Electromagnetic analysis of HTS Synchronous Machine

A model is developed to carryout electromagnetic analysis for estimation of OCC voltage in ANSYS Maxwell software. The geometrical parameters considered for model development are listed in Table 2. Figure 2, Figure 3 and Figure 4 shows the geometrical model, flux density variation and flux line distribution in the machine obtained from FEM based electromagnetic simulation respectively.

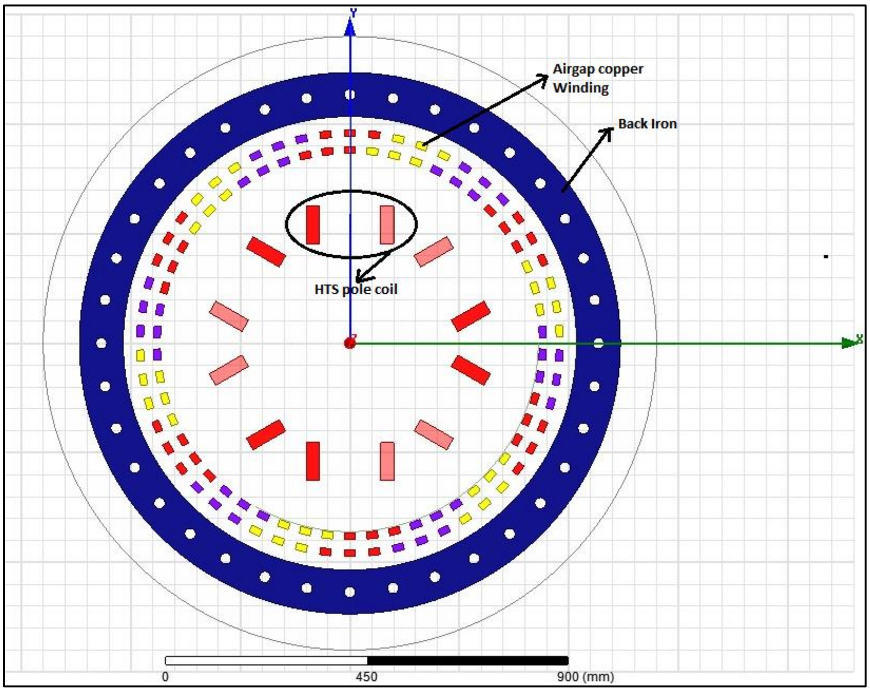

Figure 2. Geometrical model developed for electromagnetic analysis

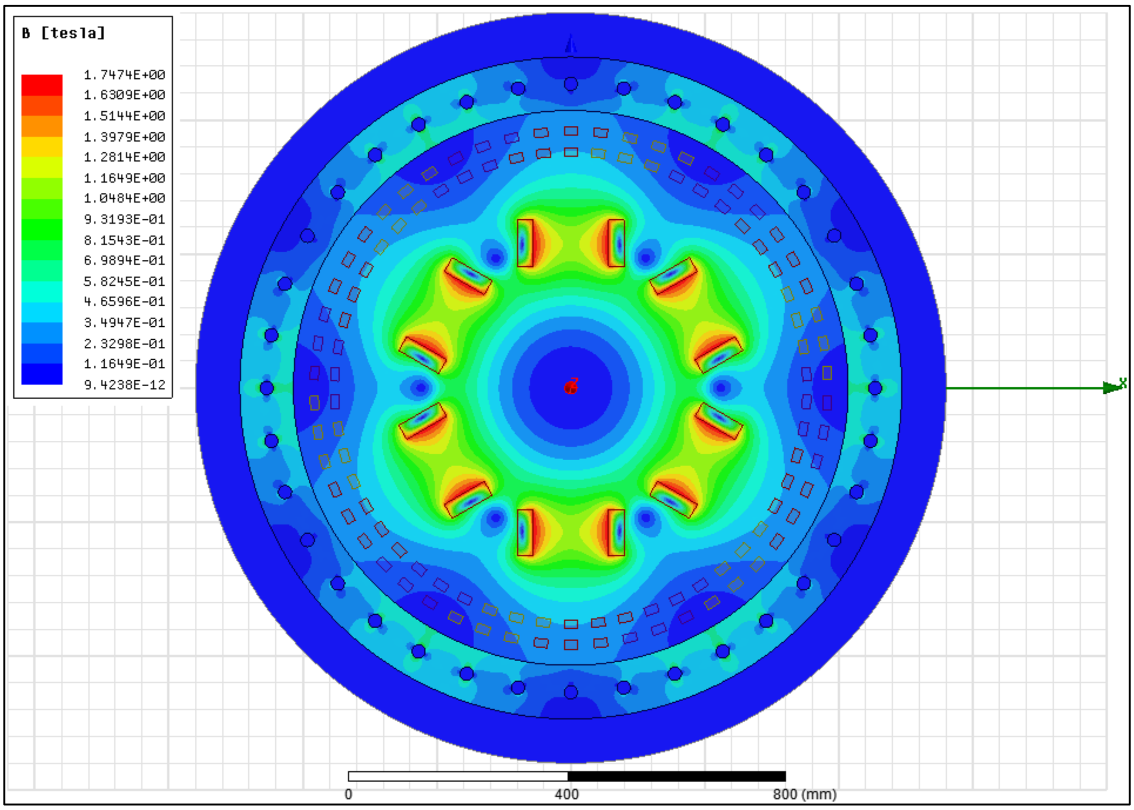

Figure 3. Flux density distribution at no-load excitation

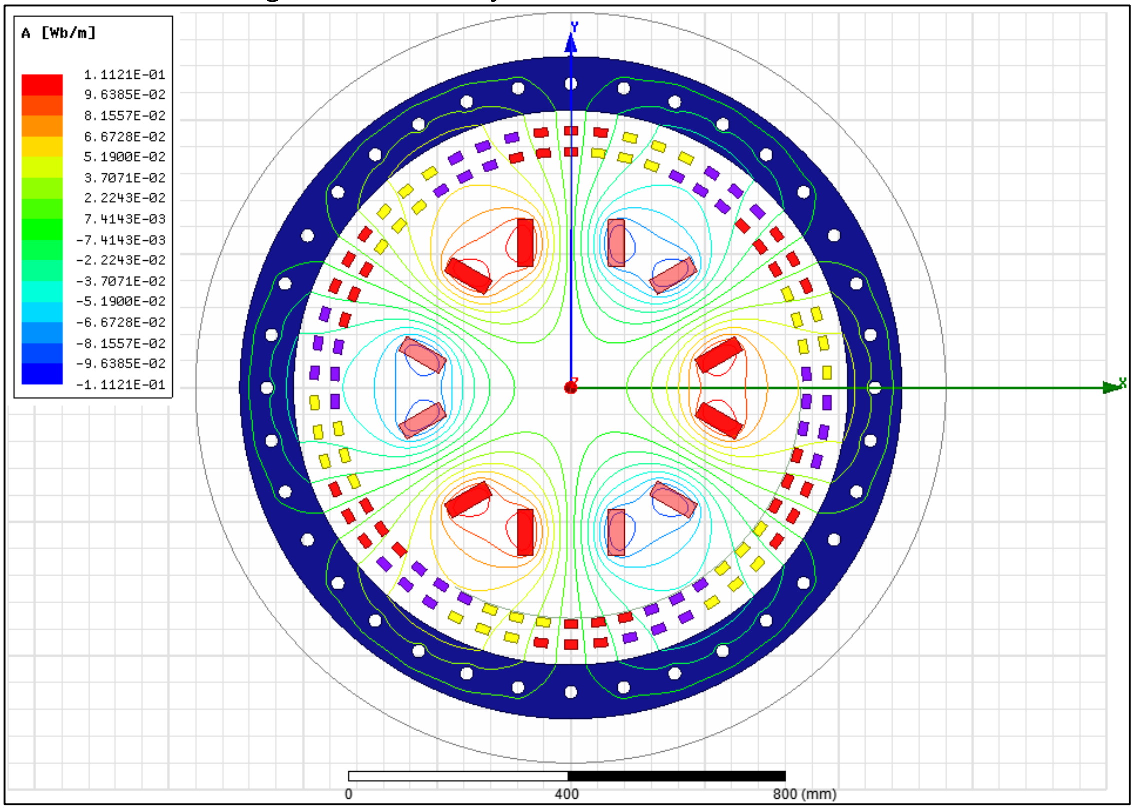

Figure 4. Flux line distribution at no-load excitation

Table 2. Geometrical parameters of HTS synchronous machine

S.No.	Parameters	Values
1	No of slots	54
2	Stator ID	865 mm
3	Rotor OD	626 mm
4	Power factor	Unity
5	Pole coil type	HTS Double pancake coil
6	Stator winding	Double layer
7	Ampere turns/pole	2,25,000 AT
8	Core length	500 mm
9	HTS tape width	4mm

The following equations are used for calculating the open circuit characteristic voltages. The fundamental induced e.m.f of a phase is given by

$$E_{ph1} = 4.44\, k_{d1} k_{p1} f_1 T_{ph} \varphi_{u1} \qquad (1)$$

where,

k_{d1} is the stator winding distribution factor for fundamental frequency,
k_{p1} is the stator winding pitch factor for fundamental frequency,
f_1 is the fundamental frequency in Hertz,
T_{ph} is the number of series turns per phase of the stator winding,
φ_{u1} is the fundamental useful flux per pole in Webers.

The useful flux [φ_{u1}] is defined as the flux linking the stator winding causing the induced voltage. This flux is lesser than the total flux by the amount of leakage flux. The expression for the useful flux per pole is given by,

$$\varphi_{u1} = (\int B\, dl) L_I S_f M_f \qquad (2)$$

where,

φ_{u1} is the useful flux per pole in Webers,
B is the flux density magnitude in Tesla,
L_I is the net length of iron in meters,
S_f is the stacking factor,
M_f is the model factor.

The OCC voltage calculated by analytical design calculation and FEM based electromagnetic simulation at rated speed are compared and given in Table 3.

Table3. Comparison of open circuit voltage

Parameter	Analytical design value	EM Computed value	% error
Open circuit voltage	239.6 V	240.98 V	0.57%

The % error in open circuit voltage computation is 0.57 and is quite acceptable. By doing this analysis it is confirmed that the pole coil ampere turns requirement is 2,25,000.

4. Estimation of parallel and perpendicular magnetic field values on HTS tape of pole coils The ampere turns requirement in the pole coils is confirmed through electromagnetic analysis and finalized as 2,25,000. The parallel and perpendicular magnetic fields at pole coil geometry are estimated by drawing geometrical boundary lines on pole coil as shown in Figure 5.

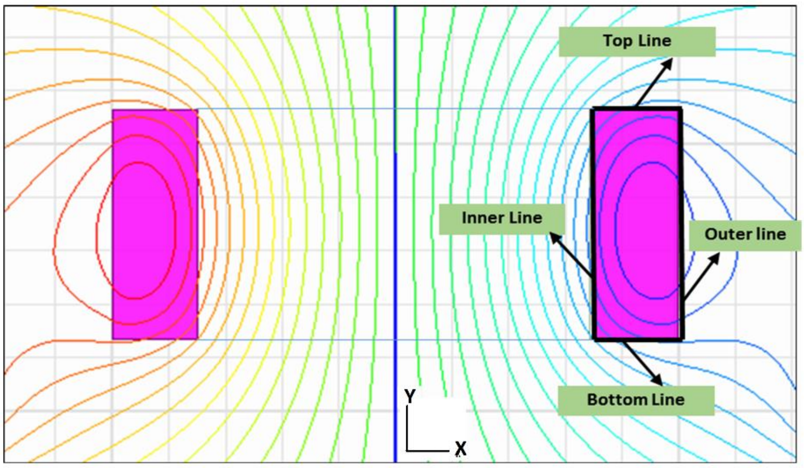

Figure 5. HTS pole coil and corresponding geometrical lines considered for estimation of parallel and perpendicular magnetic flux densities

Figure 6 shows the flux density variations across the geometrical boundary lines (the top, bottom, inner and outer lines are shown in Figure 5). The maximum magnetic flux density parallel (B||) and perpendicular (B⊥) on various boundary lines are given in Table 4. From Table 4, it is clear that the maximum perpendicular magnetic flux density on HTS tape is 1.37 T and parallel magnetic field flux density is 1.72 T. By considering suitable safety factor, the perpendicular and parallel magnetic flux densities on HTS tape are considered as 2T and 3T respectively.

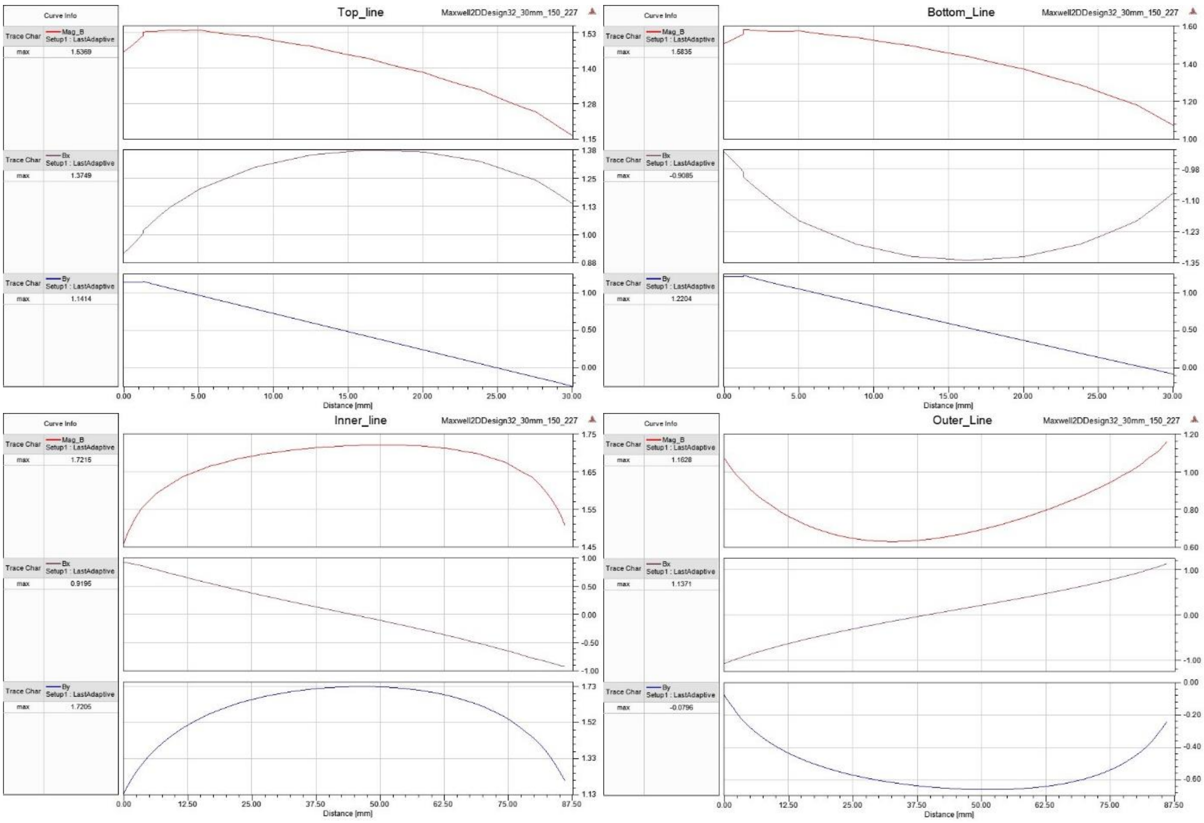

Figure 6. Magnetic flux density variation for HTS pole coil along all four geometrical boundary lines

Table 4. Maximum perpendicular and parallel magnetic flux density values on HTS pole coil tape.

Geometrical boundary line	Maximum perpendicular magnetic flux density	Maximum parallel magnetic flux density
Top line	1.37 T	1.14 T
Bottom line	0.90 T	1.22 T
Inner line	0.91 T	1.72 T
Outer line	1.13 T	0.07 T

5. Selection of HTS tapes for pole coil development:

The criterion for selection of HTS tape majorly depends on operating temperature, operating current and applied magnetic field. The applied magnetic field on HTS tapes of a coil is estimated using the results of electromagnetic simulation of HTS synchronous machine in six pole configuration with 2,25,000 AT. Considering the SuperPower® make YBCO based SCS4050-i-AP HTS tape and operating temperature of 30 K, the operating current and turns required for HTS pole coil development are calculated. SuperPower® make YBCO tape specifications are given in Table 5.

Table 5. YBCO tape specifications [4]

Specification	Details
Type of HTS tape	YBCO (SCS4050-i-AP)
Critical current (Ic)	110 A @ 77 K, self-field
Average width of tape	4.05 mm
Average thickness of tape	0. 161 mm
Insulation / wrapping	Polyimide
Stabilizer	Copper
Critical bending diameter	11 mm (room temperature)
Critical tensile stress	550 MPa

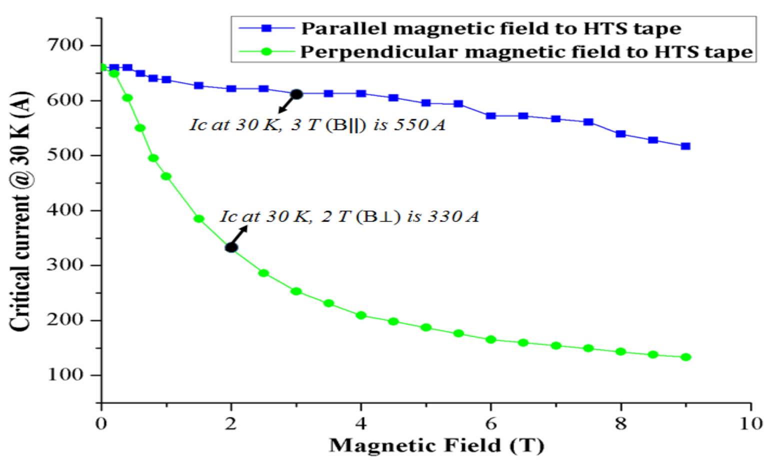

Figure 7. Critical current of 2G-HTS tape (SCS4050-i-AP) at 30 K under perpendicular and parallel magnetic fields (computed based on the data provided by SuperPower® Inc. USA)

By considering the operating current of HTS tape in the double pancake coil at 30 K as 150 A (DC), from Figure 3, it is observed that the critical currents (I_c) of HTS tape at 30 K are 330 A and 550 A under 2 T perpendicular magnetic field (B⊥) and 3 T parallel magnetic field (B||) respectively. While, the operating current of HTS pole coil is 150 A which is 0.45 times of critical current (330 A) at 2 T perpendicular magnetic field and 0.27 times of critical current (550 A) at 3 T parallel magnetic field.

Based on the above, it is confirmed that YBCO (SCS4050-i-AP) HTS tape is quite safe and suitable for the development of HTS field coils of the given synchronous machine and the turns required for each pole coil are 1500 turns. By increasing the operating current of coil above 150A, the turns can be further reduced with a compromise on safety factor.

6. Development of HTS pole coil:

A pole coil was developed with YBCO (SCS4050-i-AP) HTS tape with 1500 turns. The pole coil was manufactured by stacking five double pancake coils. Each pancake coil consists of 300 (2 x 150) turns. The picture of developed HTS pole coil is shown in Figure 8 . The developed HTS pole coil was tested for superconductivity at 77K and for 150 A operating current (DC) at 30 K. The I-V characteristics of HTS pole coil up to operating current is shown in Figure 9.

Figure 8. Developed HTS pole coil

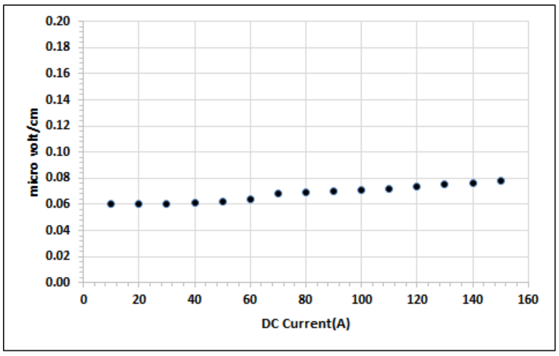

Figure 9. I-V Characteristics of HTS pole coil at 30K

7. Conclusion

A 0.2 MW HTS synchronous machine was modelled and simulated using electromagnetic analysis based on the input parameters obtained from analytical design to estimate the rated open circuit voltage. The electromagnetic field analysis of pole coil resulted in the estimation of maximum operating flux density of 2 T for B⊥ and 3T for B∥ . Considering 30K operating temperature, YBCO based SCS4050-i-AP HTS tape and suitable safety factors, operating current was selected as 150 A for development of HTS pole coil. Further, the calculations also gave the number of turns per pole coil to be 1500. Through this analysis, specifications are finalised as 2,25,000 Ampere turns (150 A X 1500 Turns) for development of HTS pole coil. The HTS pole coil (stack of five double pancake coils) is developed and tested at 77K for superconductivity and at 30 K for operating current of 150 A (DC) to use in 0.2 MW HTS synchronous machine. The parallel and perpendicular magnetic field obtained for the operating current of 150 A at 30 K is well within the safe zone with respect to quenching of HTS coil.

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