Modeling and measurements of circular and trapezoidal shape HTS coils for electrical machines applications

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Abstract. Axial Flux Electrical Machines (AFEM) with good power-to-weight and diameter-to-length ratio and high efficiency are very attractive for most industrial and power applications. Investigations with both theoretical and experimental methods of ac losses are important for a reliable prediction of dissipation mechanisms in AFEM. In this paper, simulated and measured results for both critical current (I_c) and transport current losses (P_{loss}), obtained on HTS coils, are reported. To investigate shape effects, double pancake coils with variable turns and shapes have been manufacted. Commercial grade $ReBa_2Cu_3O_{7-x}$ (Re = Y or rare earths, ReBCO) tape and epoxy resin has been used for coil winding. A magneto-static 2D finite element model (FEM) for the coils cross section, and a lumped model for AC losses estimations, have been implemented. The agreement among measured and simulated results are satisfactory.

Keywords: HTS (High Temperature Superconductors), AFPM (Axial Flux Permanent Magnets), I_c (critical current), sc (superconductors), HTS 2G (second generation HTS)

1. Introduction

Y-based second generation high temperature superconductors HTS are interesting candidates for AFPM electrical machines applications. To increase electrical loading in the design of Axial Flux Permanent Magnets (AFPM), the use of HTS coils for armature winding is a reasonable choice. HTS coils are typically placed in the stator disk and, in order to maximize the magnetic flux coupling, usually have trapezoidal or circular shapes according to the rotor disk permanent magnet's. HTS tapes AC losses have a significant impact in these applications, and an their estimation gives a better understanding of the overall output power. The Superconductivity Group at ENEA Research Center of Frascati is currently investigating the electromagnetic properties of HTS coils internally manufactured at LN_2 temperature with a particular focus on the AC losses. In this paper we describe a DC FEM code model and a lumped constant AC model for HTS coils. Experimental data have been obtained by electrical methods, and a good agreement with the numerical simulations has been achieved for both DC and AC models.

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2. HTS coils preparation

Two different types of HTS coils, A and B (Fig. 1a), have been assembled in double pancake configuration using YBCO Copper laminated certified straight tape Amperium® (4.8 mm x 0.2 mm and self-field critical current Ic>100 A at 77 K). Each coil has been wound around a PVC core side by side with one continuous tape under tension control (2 N); starting at mid-section and so avoiding internal coil electrical joints. Both coils, A and B, have been wet-wound impregnated by diluting Stycast resin in ethyl alcohol 2:1 but with different turns number (10 and 46) and shape (circular and trapezoidal) respectively [1].

Figure 1 (a). HTS coil A and coil B

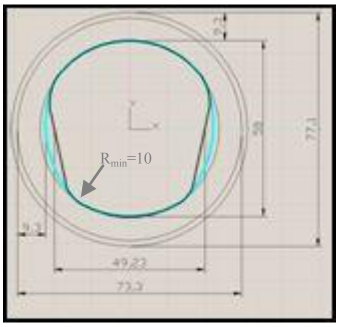

Figure 1 (b). All dimensions in mm. Coil B - height = 11 mm, maximum bending = 10 mm .

The material used for impregnation has been treated according to its own preparation process, high temperature curing has not been performed, all samples being dried at room temperature. During HTS tape winding, the YBCO tape has been outward oriented inter-layering an epoxy resin (Stycast) for electric insulation and mechanical robustness. Coil A configuration parameters are: inner radius (R_i = 20 mm), outer radius (R_{out} = 22.3mm), height (h = 11 mm); coil B dimensions are reported on Fig. 1 (b).

3. DC and AC measurements

To estimate the critical current, I_c, of each HTS coil, current–voltage characteristics at 77 K and self-field condition has been measured with electrical method and the probes placed before any electrical joint. I_c = 100 A and I_c = 75.6 A for coil A and B respectively, have been obtained. AC transport current losses (P_{Loss}) versus rms current (I_{rms}) measures, for each coil at 77 K and various frequencies, have been carried out with the electrical method and are reported in Fig. 2 (a), 2 (b). In particular, P_{Loss} has been obtained multiplying the real rms voltage V_{coil} component, from the lock-in amplifier, with the supplied I_{rms}. An outlook of the obtained results, at a meaningful frequency of 50 Hz, is shown in Fig. 3 (b).

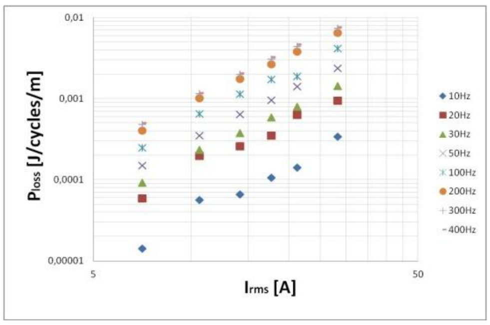

Figure 2 (a). P_{loss} vs I_{rms} @ 77 K and various frequencies for Coil A

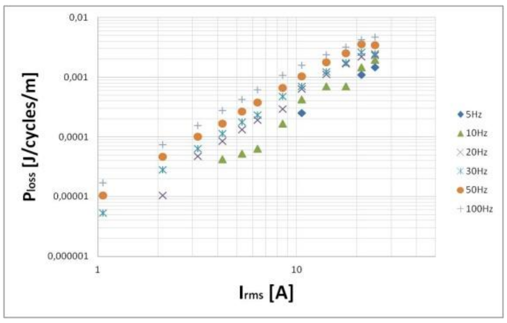

Figure 2 (b). P_{loss} vs I_{rms} @ 77 K and various frequencies for Coil B

4. AC losses lumped model

A simple model for AC losses estimation [2] can be used to explain our measurement results. Hysteretic losses, both of the superconductor and the Ni-W substrate, are modeled by a frequency linearly dependent resistance $R_{sc} = R_0 \cdot f$. The losses on the copper based alloy matrix stabilizer are modeled by a resistance R_{Cu} and the lumped model circuit is shown in Fig. 3 (a). $R_0 = 5 \cdot 10^{-5}$ [Ω/Hz] is the only data fitting parameter in our model and a good agreement with the measured data has been achieved (Fig.3 (b)).

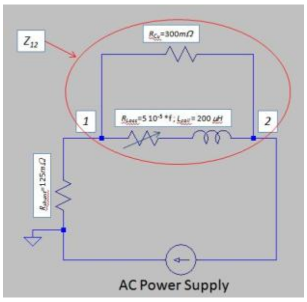

Figure 3 (a). Lumped equivalent circuit for AC losses estimation

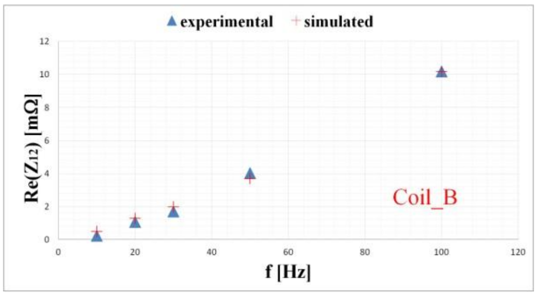

Figure 3 (b). $Re(Z_{12})$ vs frequency @ 77 K and $I_{rms} = 35$ A for Coil B

5. FEM model: 2D approximation

An YBCO double pancake model is implemented using a finite element software (COMSOL Multiphysics 4.3). A 2D axial symmetrical H-formulation has been applied as in Ref.[1]. Tape characteristic properties have been used to improve experimental and data agreement [1].

An elliptical composition of parallel and perpendicular behavior, both of the critical current and the n-value, have been introduced for magnetic anisotropic YBCO tapes modeling:

$$I_c(B,\theta) = \sqrt{I_{c\perp}(B)^2\cos^2\theta + I_{c\parallel}(B)^2\sin^2\theta}$$

and

$$n(B,\theta) = \sqrt{n_{\perp}(B)^2\cos^2\theta + n_{\parallel}(B)^2\sin^2\theta}$$

$\theta \equiv$ angle between c-axis (i.e. current direction) tape and magnetic induction B. n-value, self-field and temperature dependencies of critical current have not been modeled.

The 2D axial symmetrical geometry ((r, z) cylindrical coordinate system describing coil cross section (Fig.4) has coil current I_ϕ parallel to the electric field $E_\phi = \rho J_\phi$. The parameter ρ is a position function given by (3) inside the material, while on the outside $\rho = 10^5$ Ωm (to speed up numerical calculations, air resistivity [3] was chosen lower than the real value and much higher than the HTS resistivity in dissipative regimes). The YBCO tape E-J power law is:

$$\rho(B,\theta) = E_c/J_c(B,\theta) \times \left(J_\phi/J_c(B,\theta)\right)^{n(B,\theta)-1} + \rho_0 \quad (1)$$

where a ρ_0 value of 10^{-16} Ωm, i.e. the Thermally Activated Flux Flow resistance (TAFF) at 77 K of HTS 2G tape [6] has been used in our DC simulations. A code computed I-V curve of double pancake coil has been carried out to test the model. In the 2D simulation, the current is ramped up to a value I and then kept constant for 1 s (in order to relax the calculated voltage). As can be seen in Fig.3, the experimental data $I_c = 75.6$ A are roughly consistent with simulation data $I_c = 78.6\ A$; discrepancies are due to the flattening of the coil section along the x-coordinate (Fig. 1(b)) producing a strength magnetic field higher than the corresponding cylindrical configuration used in the simulation. In any case, the approximation being quite good (only a 4% error on I_c) validates our model and opens the possibility for AC losses estimation. Finally, the total magnetic field B, when the supplied current is equal to the critical value of coil_B, is shown in Fig.4.

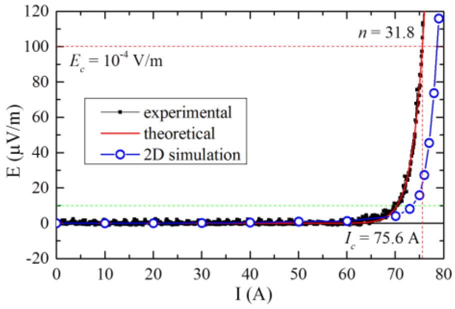

Figure 3. Comparison between the I-V curve measured, theoretical and simulated in 2D for coil_B at T = 77 K

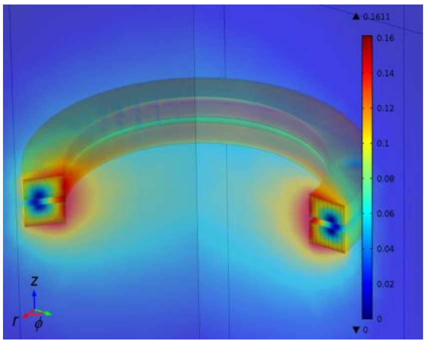

Figure 4. Snapshot of the magnetic field intensity B (T) simulated for coil_B at $I=I_c$

6. Conclusion

In this paper, an improved 2D finite element model, based on the *H*-formulation and implemented in COMSOL Multiphysics, and a lumped model have been described. The models were used to investigate the electromagnetic properties and calculate the AC losses in different shape HTS coils Stycast wet-wound impregnated. The transport current losses and the critical current density of the coils were measured. Experimental and simulation results are in good agreement. Consequently, the results can be used for AC losses computation in cases of AFPM electrical machines with HTS armature winding.

7. References

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