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Coil optimization for HTS machines

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Abstract

- This paper presents topology optimization of a HTS racetrack coils for large synchronous machines with HTS excitation winding. The topology optimization is used to acquire optimal coil design for the excitation system for machines with 3T air-gap flux density. Several tapes are evaluated and the optimization results are discussed.
Article investigates possibility of combination of different HTS in the coils. The optimization algorithm is formulated to minimize the cost HTS of coils. The results seems to be in favor of 1G tapes.

HTS machines design

Recommended HTS machine design varies for application which machine is intended for. The common characteristic for all HTS machines and one of their main benefits, is the power density which could be several times larger than in conventional machines. The two designs, which the HTS synchronous machines are converging, are salient pole machine with conventional armature winding and non salient multi-pole machine with air-gap armature winding. Both designs are shown and described in the Fig.1.

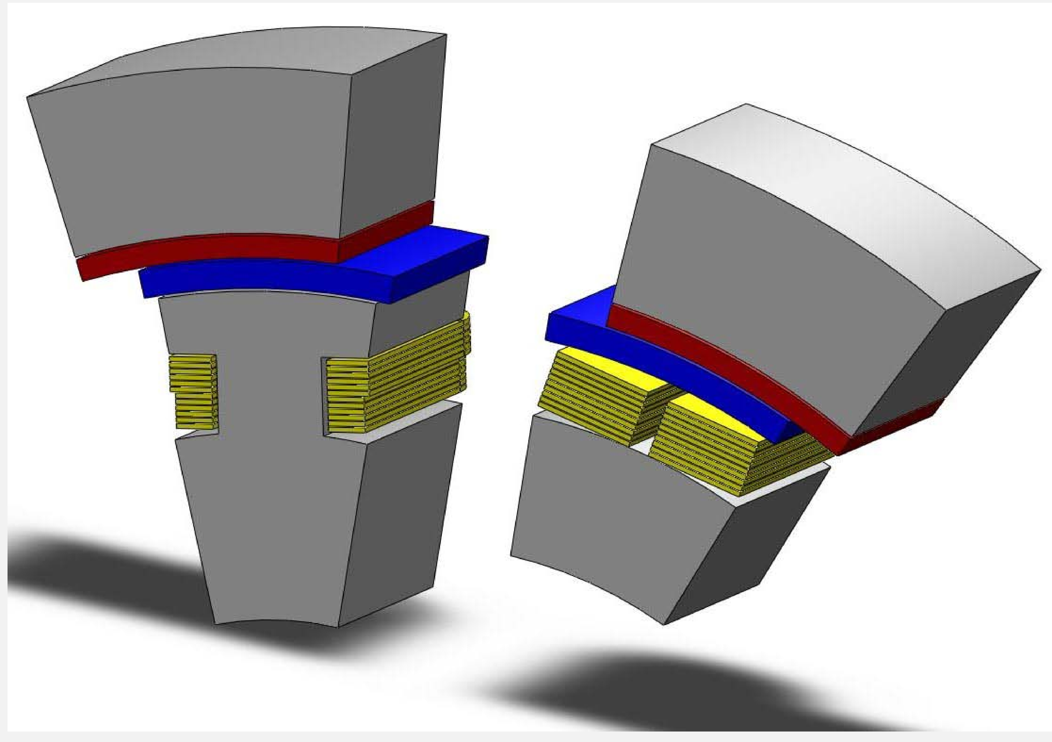

Fig.1 Conceptual design of one pole section for salient (left) and non-salient (right) synchronous machine with air-gap winding. The magnetic steel is gray, armature winding is dark red, thermal insulation (vacuum chamber, spacers, radiation shields) is blue and space for HTS coils is donated with yellow.

HTS Coil design

HTS tapes, both 1G (BISCO) and 2G (coated conductors), are coming in the form of the thin tapes (0.2 mm - 0.4 mm) with different widths (5 mm as a most common). Recently, the very thin CC tapes (<0.1mm) have became available. If the coated insulation is applied to this tape, this would yields cross sectional area of only 1 mm^2 for insulated tape which allows compact coil design. This tape corresponds to the most expensive tape and it is available in limited length. The larger length of the tapes are available only for the 1G tapes, thus putting additional constrains on large scale application.

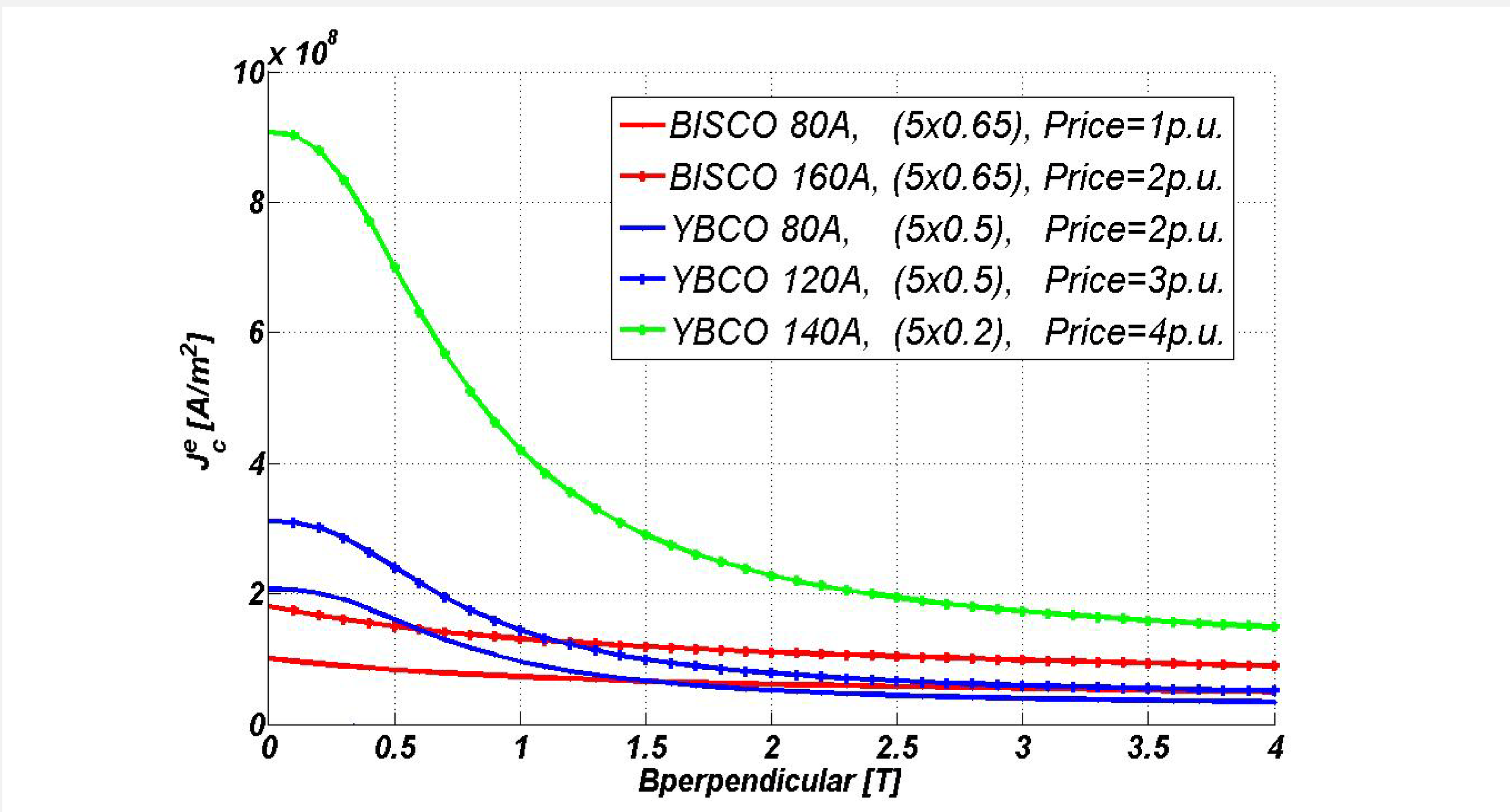

Fig. 2. Estimated engineering current density for 1G and 2G coils at 20 K. Legend reads the HTS type, I_c@77K in self field, estimated dimensions of cross section of insulated HTS tapes in [mm] and estimated price of the tapes, all normalized to the price of 1G-80A (BISCO-80A). The insulation of the tapes is assumed to be 0.3 mm for glass fiber and 0.15 mm for coated insulation.

FE model for coil optimization

The model geometry of a conceptual machine used for coil topology optimization is shown in Fig. 3. The machine is 16 poles, non salient with air-gap winding. The FE model is reduced to one pole sector using machine symmetry. The magnetic fields are calculated in steady state using vector potential formulation of Maxwell equations. The nonlinear material properties of ferromagnetic steel, silicon steel M800-50, are implemented. The optimization space domain corresponds to the 7 double pancake coils. Each double pancake coil was presented with one rectangle, wide 10 mm.

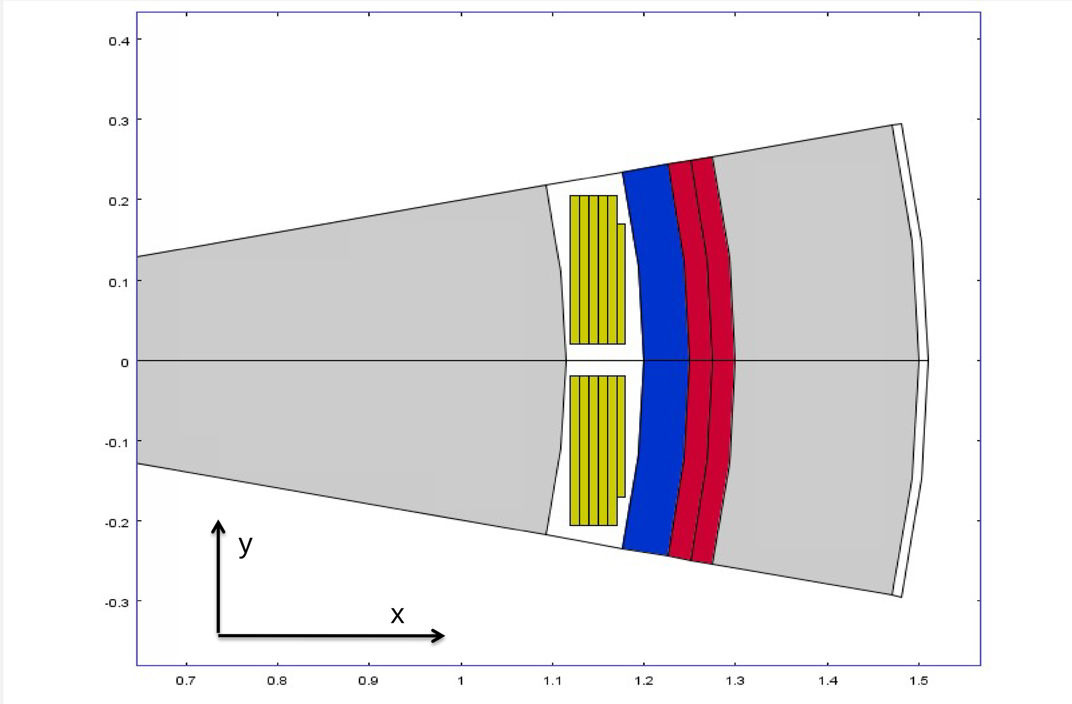

Fig.3 Simplified model of a synchronous HTS machine with air-gap winding. The magnetic steel is gray, armature winding is dark red, thermal insulation (vacuum chamber, spacers, radiation shields) is blue and space for HTS coils is yellow.

$$\hat{B}_{\perp}^{[coil,j]}(y) = \frac{1}{w_{tape}} \int_0^{w_{tape}} {}^{j}opt \cdot \left| B_{\perp}(x,y) \right| dx \qquad \text{Eq.1}$$

$$B_{\max\perp}{}^{j} = \overset{\Omega_{coils}}{MAX} \left(\hat{B}_{\perp}^{[j]}(y) \right) \qquad \text{Eq.2}$$

Optimization formulation

Topology optimization is used in structural studies to ensure minimum material and cost and increase robustness of the structure, especially in an application where over sizing caries high cost penalty (airplane industry).

Objective function will have several contributions in order to formulate the optimization problem properly. The Eq. 3, contains the generalized objective function which is minimized .

$$\min \ Objectiv = \sum_{k=1}^{3} obj_k \qquad \text{Eq.3}$$

$$0 \le {}^{j}opt(x,y) \le 1 \qquad \sum_{j=0}^{N_{HTS}} {}^{j}opt(x,y) \le 1$$

If the optimization variable, ${}^{j}opt$ is 1, the current carrying HTS will be present at that coordinates and if it is 0, not. Also the sum of all variables at specific coordinate need to be either 1 or 0, corresponding to the statement that the same space could have only one tape. However, since it is not possible to constrain the optimization variable in the Comsol to only binary values, term obj_1 panelize the all values in between. Obj_2 and Obj_3 are corresponding to 3 T air gap flux condition and price of HTS contribution.

$$obj_1 = \sum_{j=1}^{N_{HTS}} \left(10^2 \int_{\Omega_{HTS}} [\frac{1}{4} - ({}^{j}opt - \frac{1}{2})^2] \, d\Omega_{HTS} \right) \qquad obj_2 = \left(5 \cdot (B_{r,peak}^{design} - \underbrace{2 \int_{-\pi/2}^{\pi/2} B_r \cos(\theta) d\theta_{armature}}_{first\ harmonic}) \right)^2$$

$$obj_3 = \sum_{j=1}^{N_{HTS}} \left(\int_{\Omega_{HTS}} {}^{j}opt \cdot C_j \cdot d\Omega_{HTS} \right) \qquad \text{Eq.4}$$

In the case of single HTS used in the coils, for the coils made from 2G 120A tape (with relative price of *3 p.u.*), the price was 0.135 *p.u.* The coils made from 1G 180A tape (with relative price of *2 p.u.*) , the price was only 0.0602 *p.u*. The coils from ultra thin 2G 140A tape would yield the price of 0.0627 *p.u,* offering price improvements compared to standard 2G 120A tape and almost twice more compact coils compared to 1G 180A. The cost impact of the coil space reduction is not taken into account as an overall factor in machine design, even though it could have very big impact on price of the machine in general and cause additional savings in HTS too.

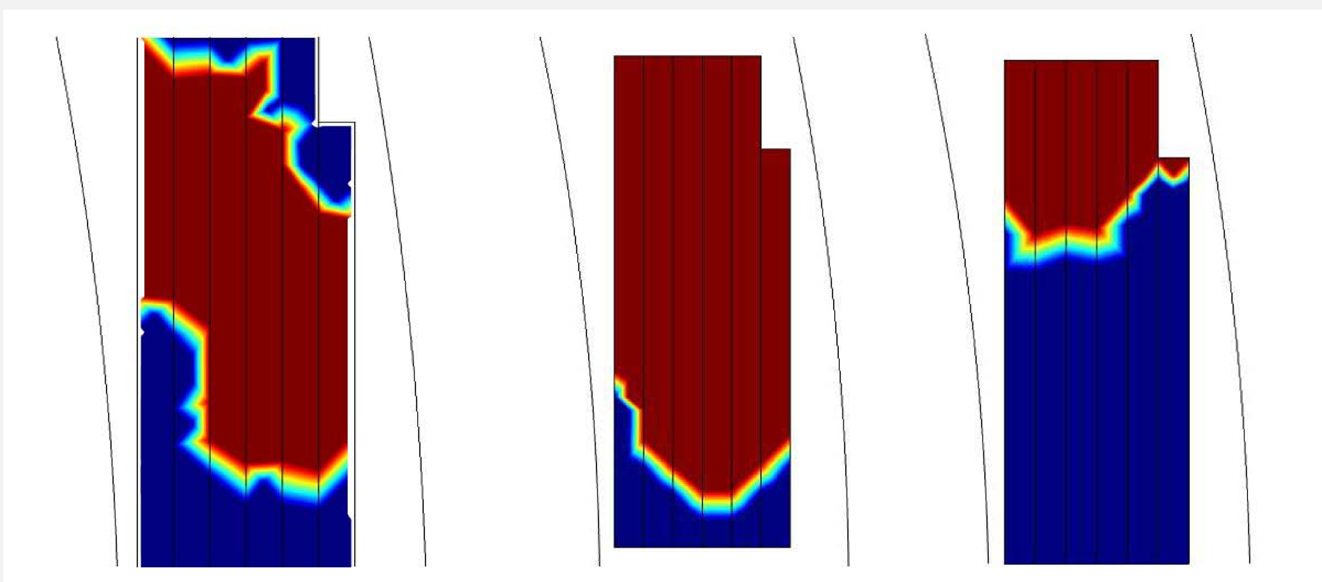

Fig.4 a) 1G-180A-2pu b) 2G-120A-3pu c) 2G-140A-4pu
Optimization results for HTS coils with single HTS type @20K. The dark red donates the current carrion domain and the dark blue not conducting space.

Multiple excitation currents

Now, in order to estimate a potential for savings in HTS material where several excitation currents are allowed, we have examined the case were each tape has its own current supply. This is far from realistic configuration, but this extreme case should yield the lowest amount of HTS. This means that each tape runs with its maximal safe *J* and give us a sense on extent of savings in ideal case.
The optimization was conducted on the coils with the same tapes as in single excitation coils. The optimization has returned 0.063 pu, 0.04 pu and 0.026 pu, as the cost for 2G-120A, 1G-180A and 2G-140A coils respectively. The optimization has confirmed that the potential for HTS reduction if multiple supplies currents are allowed. The tapes with higher nonlinear *J-B,* as 2G at 20 K, tend to have almost twofold maximal reduction in amount of HTS where in the case of 1G at 20K, the potential for savings is smaller.