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Electrical Machine with HTS winding: Analytical Design and Optimization

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Motivation

Objective:

Increase power and torque density of direct drive electrical machines using HTS

Application area

- Marine propulsion , wind turbine generators
- Automotive, Aerospace, Gas & oil…

Normal flux density $[T]$ (Field winding)

Torque $[Nm]$

$$\Gamma \propto V \,.\, B \,.\, H$$

Machine volume (air gap)

Tangential magnetic field $[A/m]$ (Armature winding)

Limits of conventional machines (copper + PM) :

- Saturation of tooth

  $B \approx 0{,}9\ T$

- Cooling systems

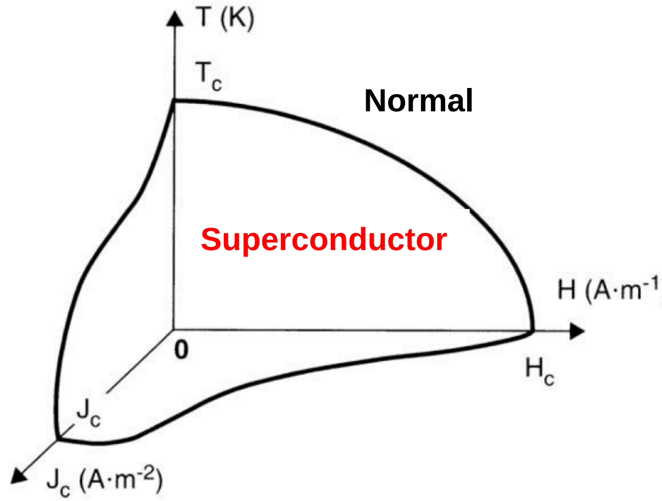
  Limited cooling factor HJ

Only the increase of B due to the field winding is considered in this work because HTS is much mature for dc applications in which losses are reduced compared to the ac case.

Constitutive law of superconductors

Superconducting state → 3 critical parameters

- Critical Temperature: T_c < *110 K*
- Critical magnetic field B_c < *few Teslas*
- Critical current density: J_c < *hundreds of A/mm²*



High Temperature Superconductors (HTS) → power law at fixed T

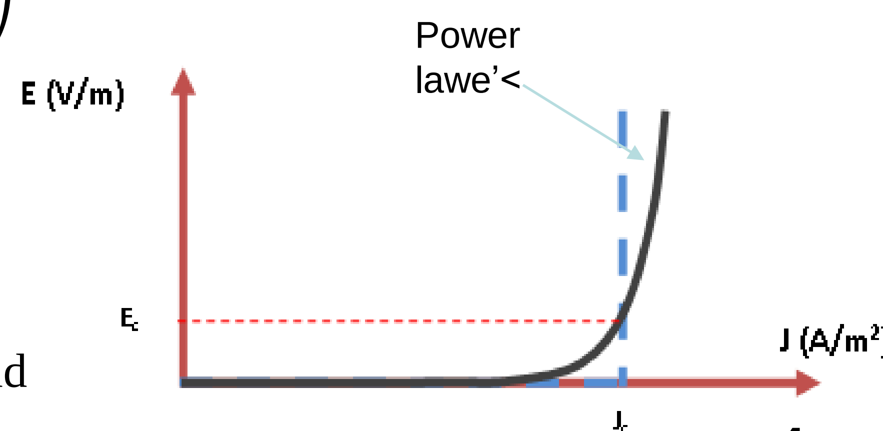
$$E = E_c \left(\frac{J}{J_c}\right)^n$$

n: index of the power law

J_c : critical current density

E_c : critical electric field $E_c = 10^{-4}\ V/m$

Both J_c and n depend on the applied magnetic field



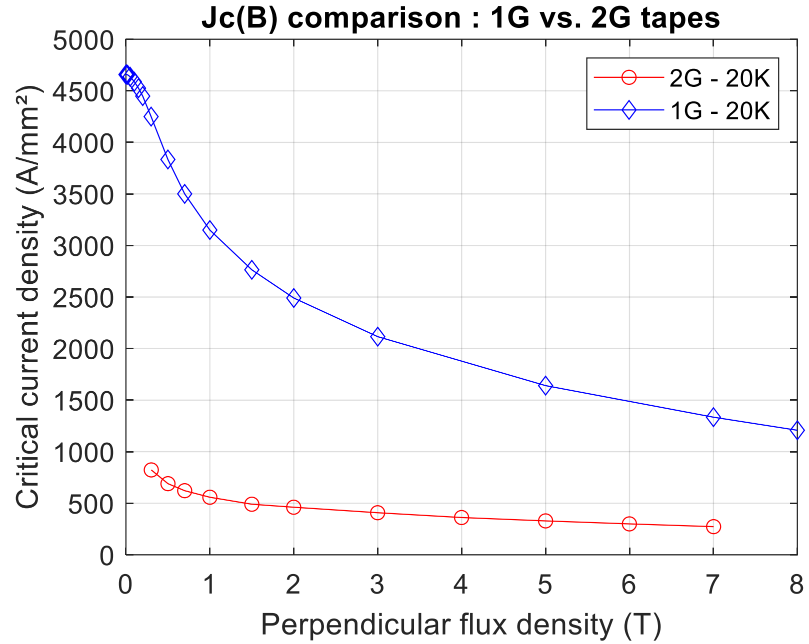
Constitutive law of superconductors

Jc(B) curves comparison

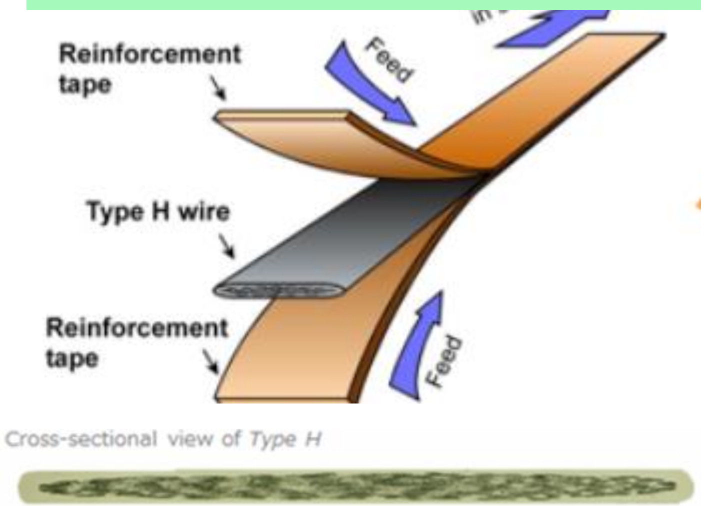
1G tape : Di-BSCCO from SUMITOMO
2G tape : YBCO from FUJIWARA

The 2G HTS tape exhibits a much higher current density compared to the 1G tape (5T and 20K):

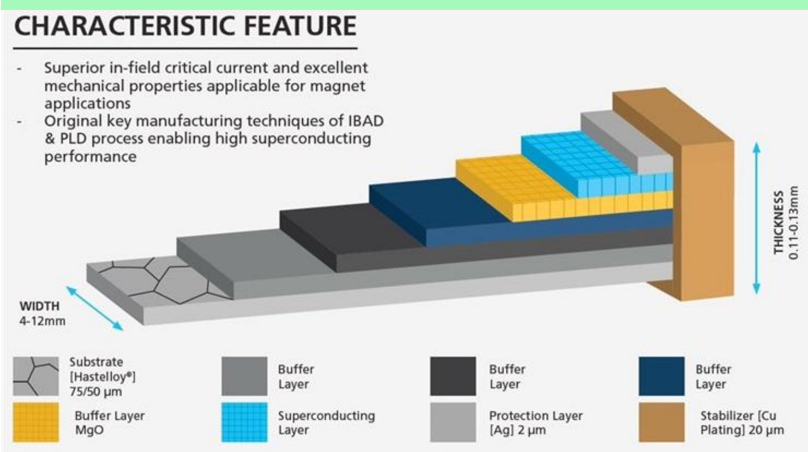
1G: **330 A/mm²** vs 2G: **1640 A/mm²**
(5 times higher)



1G Di-BSCCO H type



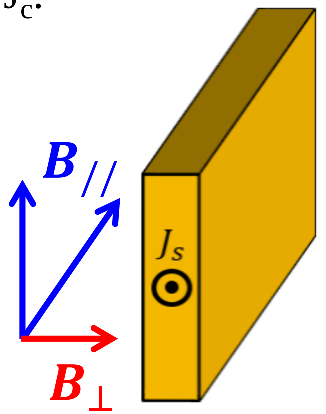
2G YBCCO FESC-SCH12 type

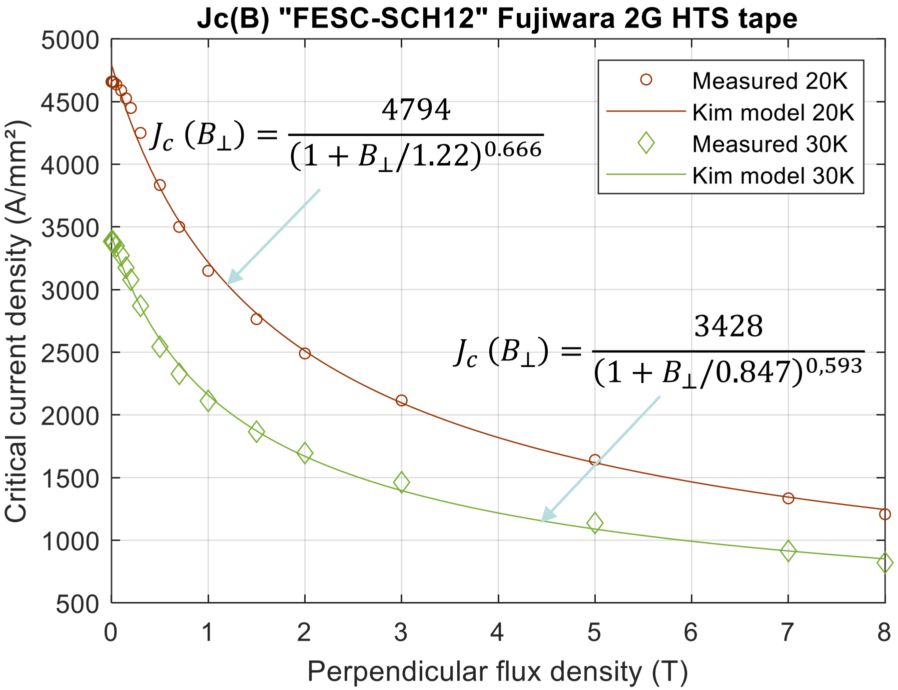


Constitutive law of superconductors

HTS tape under applied magnetic field

- J_c and n depend on B
- Anisotropic behavior: the perpendicular component $\boldsymbol{B}_\perp$ has the most important influence on the value of J_c.





Kim's model

- For modeling purposes, it is more convenient to approximate the Jc(B) curve by an analytical function.
- Interpolation of the measured data → J_{c0}, β, B_0

$$J_c(B_\perp) = \frac{J_{c0}}{\left(1 + \frac{|B_\perp|}{B_0}\right)^\beta}$$

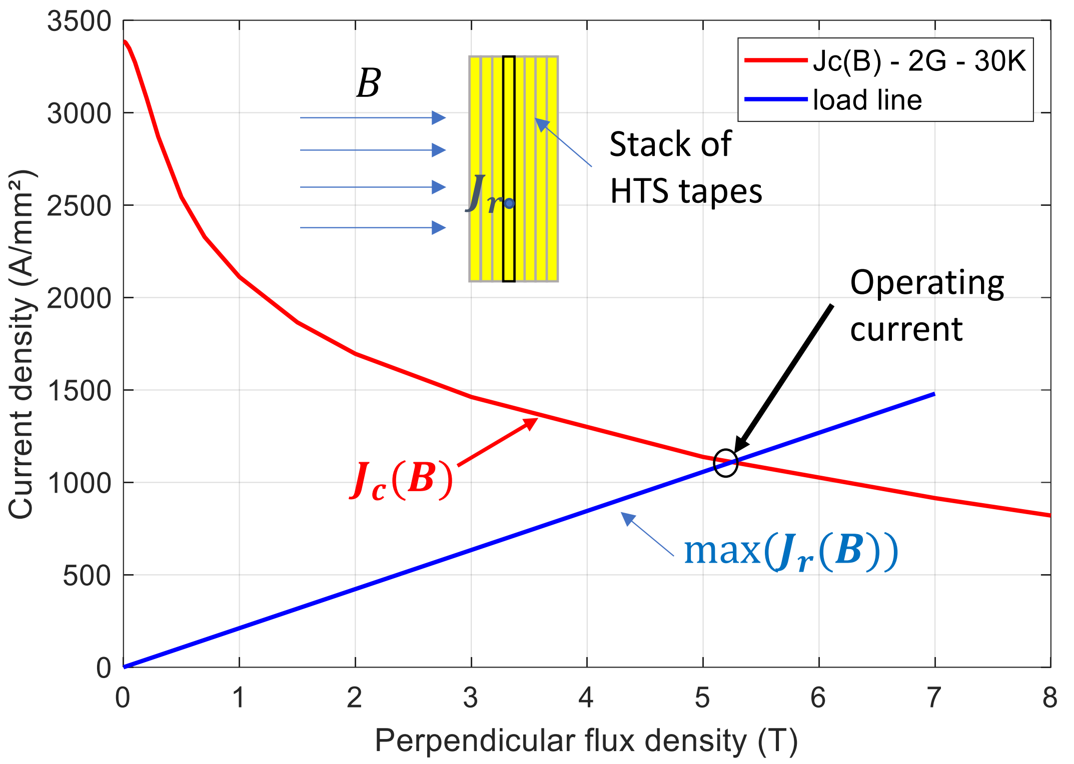
The measured data are freely available:

S. C. Wimbush and N. M. Strickland, "A Public Database of High-Temperature Superconductor Critical Current Data," *IEEE Transactions on Applied Superconductivity*, vol. 27, no. 4, pp. 1-5, June 2017, no. 8000105, doi: 10.1109/TASC.2016.2628700.

Operating current of an HTS coil

Definition of I_M (theoritical)

- Maximal allowable current avoiding thermal limits.
- Several criteria can be used (B_{max}, E_{max}, p_{max})
- The computation of I_M must be done while sizing the HTS device



Load line (or curve) method

- Easy to implement but does not consider n
- B_{max} criteria (magnetic field calculation needed)
- Take the worst case between $B_{\perp}$ and $B_{//}$

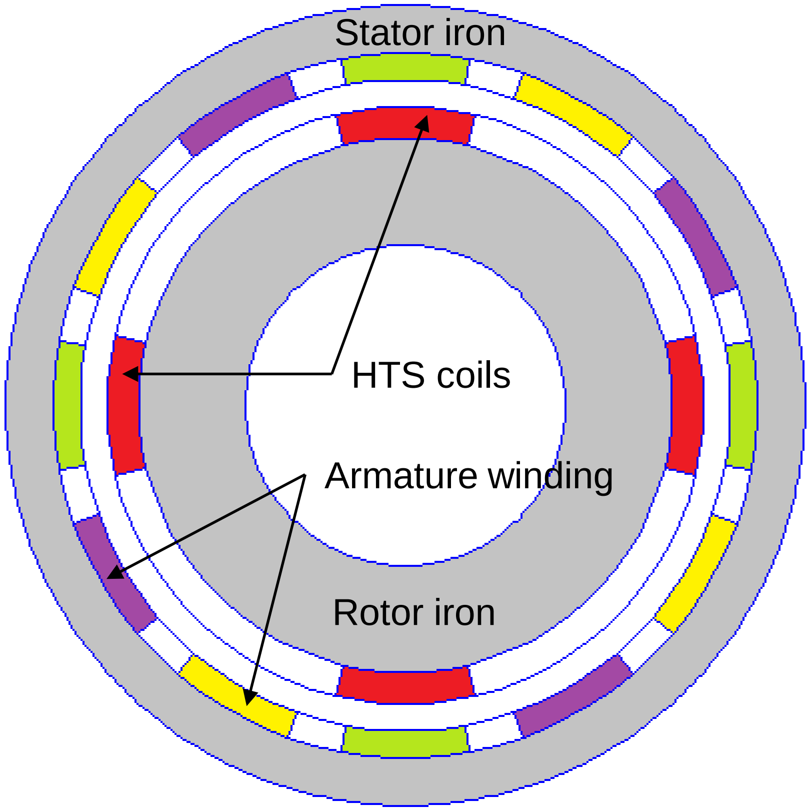
Radial field synchronous machine with HTS rotor

Radial flux machine

- Slotless HTS rotor (2G YBCO)
- Slotless 3-phase armature winding (copper)
- Back-iron made from FeCo magnetic material

Cooling technology

- Cryocoolers @ 30K.
- The rotor is placed in a cryostat so the “magnetic” airgap (cryostat wall+mechanical clearance) is equal to 8 mm



2D cross section view of HTS machine (p=2, Ne=12 slots)

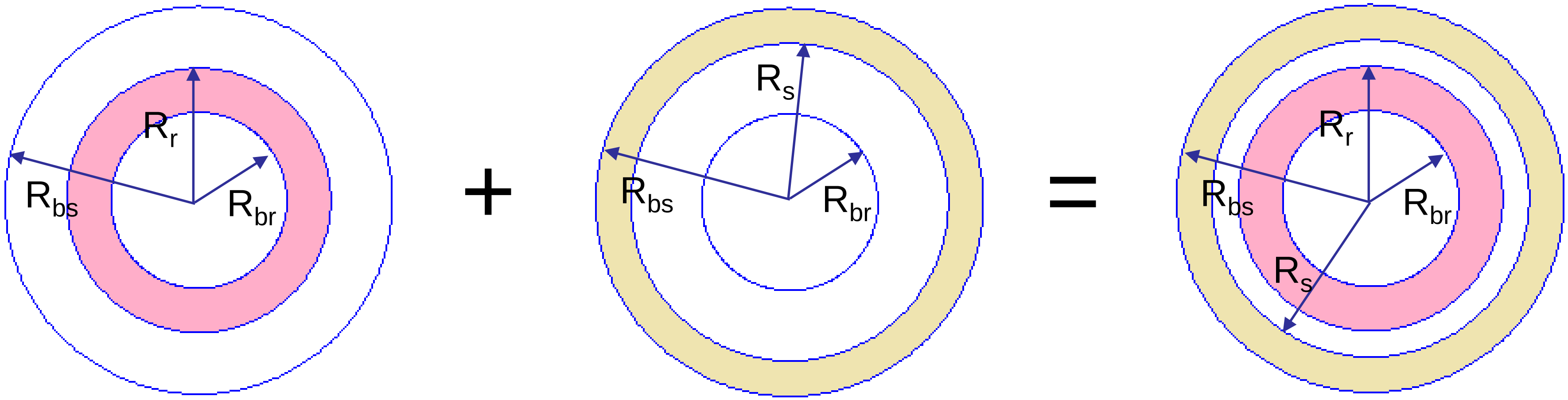
2D analytical model

Hypotheses

- Infinite iron permeability
- Only low permeability domains are considered to establish the 2D model (winding and airgap)
- The machine is decomposed into annular domains in which the solution is periodic owing the periodicity of the current density distribution in the winding

Solution

- Single source
- Vector potential formulation
- Separation of variables
- Polar coordinates
- Superposition of elementary solutions
  → Fully analytical solution

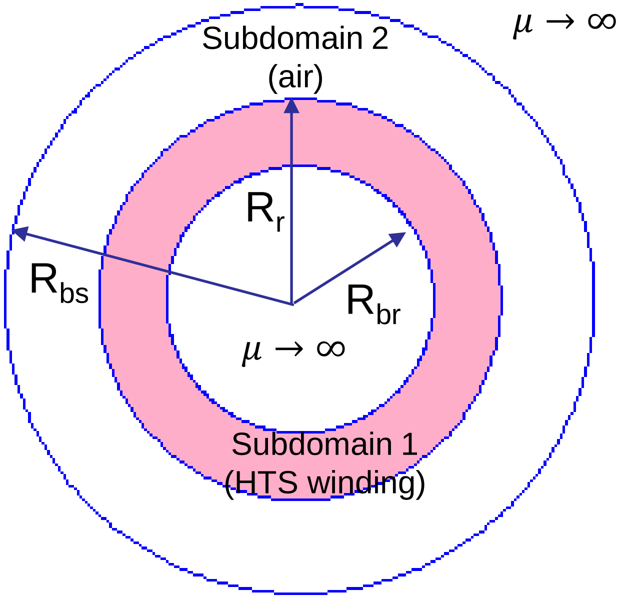


Decomposition into sub-problems in 2D

Analytical solution due to the rotor source

PDEs to solve (in polar coordinates)

- In subdomain 1 (HTS winding): $\Delta A_{r1} + \mu_0 j_r = 0$
- In subdomain 2 (air): $\Delta A_{r2} = 0$



Boundary and continuity conditions

$$\frac{\partial A_{r1}}{\partial r}|_{r=R_{br}} = \frac{\partial A_{r2}}{\partial r}|_{r=R_{bs}} = 0$$

$$A_{r1}(r = R_r) = A_{r2}(r = R_r)$$

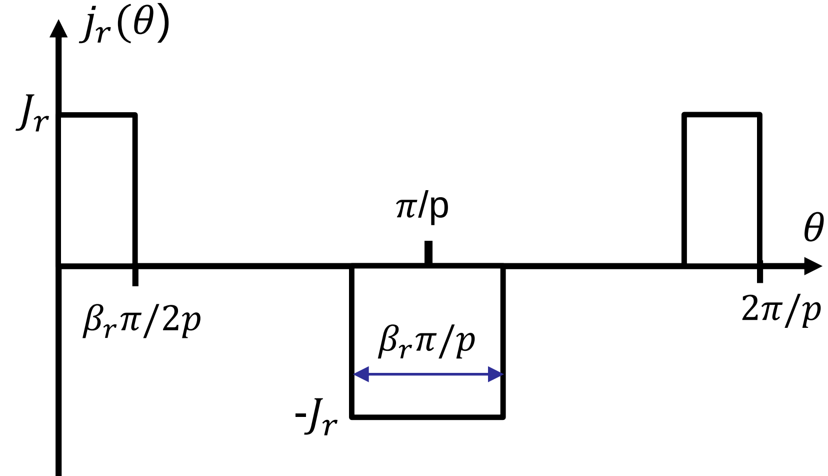
$$\frac{\partial A_{r1}}{\partial r}|_{r=R_r} = \frac{\partial A_{r2}}{\partial r}|_{r=R_r} = 0$$

Current density distribution in the HTS winding (subdomain 1)

$$j_r(\theta) = \sum_{\substack{n=1 \\ odd}}^{\infty} J_{nr} \cos(np\,\theta)$$

Where:

$$J_{nr} = \sum_{\substack{n=1 \\ odd}}^{\infty} \frac{4.J_r}{n\pi} \sin\left(\frac{np\beta_r}{2}\right), \quad 0 < \beta_r < 1$$



Analytical solution due to the rotor source

Vector potential expressions

$$A_{r1}(r,\theta) = \sum_{\substack{n=1\\odd}}^{\infty} (U_{nr}\ (r/R_{br})^{np} + V_{nr}\ (r/R_{br})^{-np} + f_{nr}(r))\cos(np\theta)$$

$$A_{r2}(r,\theta) = \sum_{\substack{n=1\\odd}}^{\infty} W_{nr}(\ (r/R_{bs})^{np} + (r/R_{bs})^{-np})\cos(np\theta)$$

Where:

$$f_{nr}(r) = \begin{cases} \dfrac{\mu_0\ \ J_{nr}\, r^2}{(np)^2 - 4} & np \neq 2 \\ \dfrac{\mu_0\ \ J_{nr}\, r^2 (1 - 4\ln(r))}{16} & np = 2 \end{cases}$$

The integration constant for the air subdomain is:

$$W_{nr} = \frac{R_r f_n'(R_r) P_{np}(R_{br}, R_r) + n f_n(R_r) Q_{np}(R_{br}, R_r) - 2R_{br} f_n'(R_{br})}{2n Q_{np}(R_{br}, R_{bs})}$$

Where: $P_k(a,b) = (a/b)^k + (a/b)^{-k}$, $Q_k(a,b) = (a/b)^k - (a/b)^{-k}$

Similar expressions can be derived for U_{nr} and V_{nr}

Analytical solution due to the stator source

The results for the stator source problem are the same as for the rotor source problem.
We only need to replace the subscript r by s in the solution of the rotor problem.
It also necessary to adapt the current density distribution to the stator armature winding.

The vector potential in the air region is:

$$A_{s2}(r,\theta) = \sum_{\substack{n=1 \\ odd}}^{\infty} W_{ns}\left((r/R_{br})^{np} + (r/R_{br})^{-np}\right)\cos(np\theta)$$

Where W_{ns} is obtained by changing the subscript r by s in W_{nr} expression given .

Torque expression:

Integration of the Maxwell stress tensor in the middle of the airgap: $R_e = \frac{R_r+R_s}{2}$.
The expression of the torque due to the 1st space harmonic n=p pole pairs is:

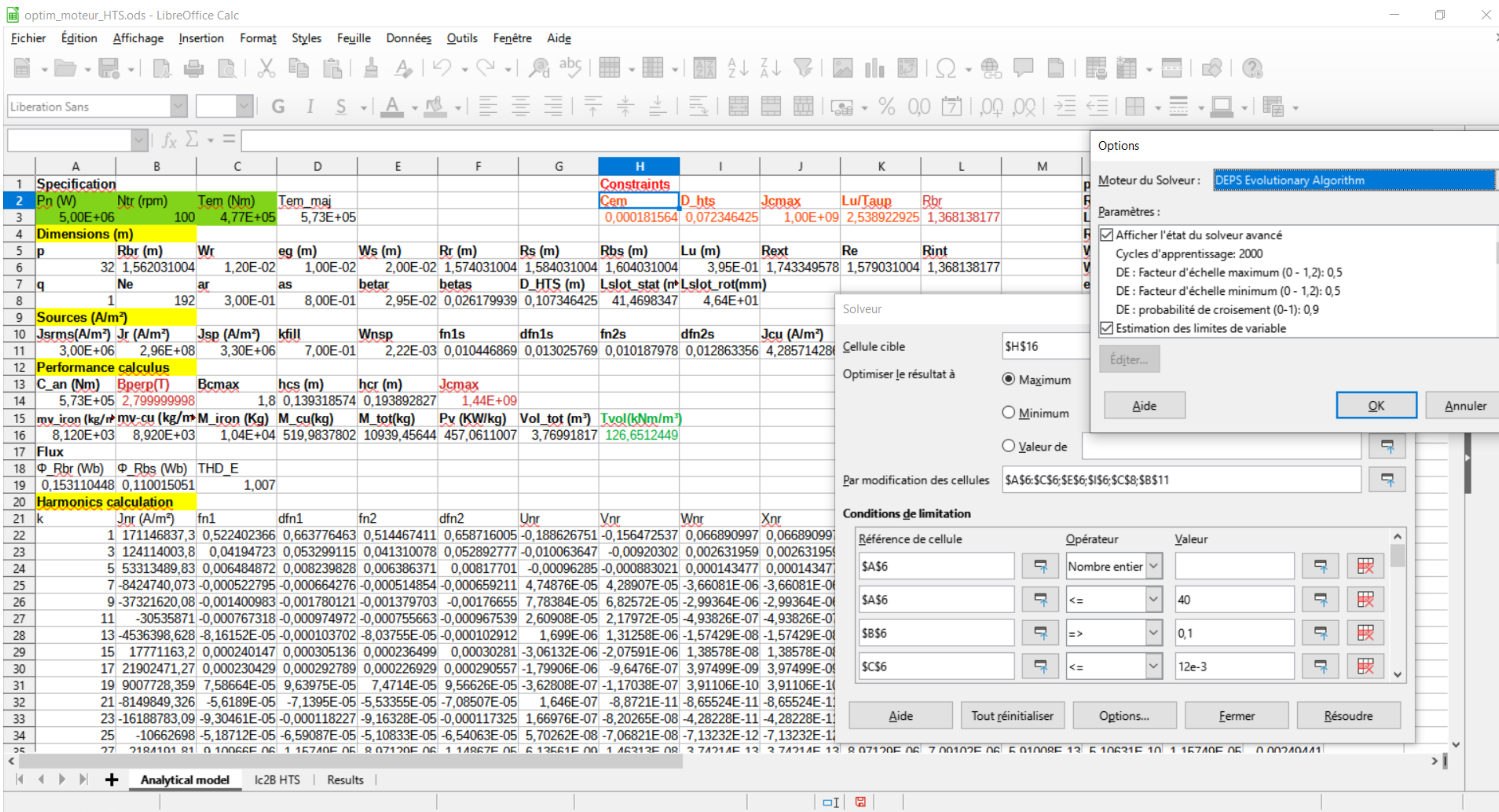
$$T_{em} = (\pi p^2 L_u/\mu_0) W_{pr} W_{ps} (P_p(R_e, R_{br}) Q_p(R_e, R_{bs}) - P_p(R_e, R_{bs}) Q_p(R_e, R_{br}))$$

Where: $P_k(a,b) = (a/b)^k + (a/b)^{-k}$, $Q_k(a,b) = (a/b)^k - (a/b)^{-k}$

Sizing a 2 MW - 5000 rpm HTS machine

Optimization tool - Office Calc interface with solver

- Single objective constrained optimization using GA-PSO under Libreoffice calc spreadsheet
- Objective is to maximize volumetric torque density



Sizing a 2 MW - 5000 rpm machine

Results for 2G HTS tapes @ 30K

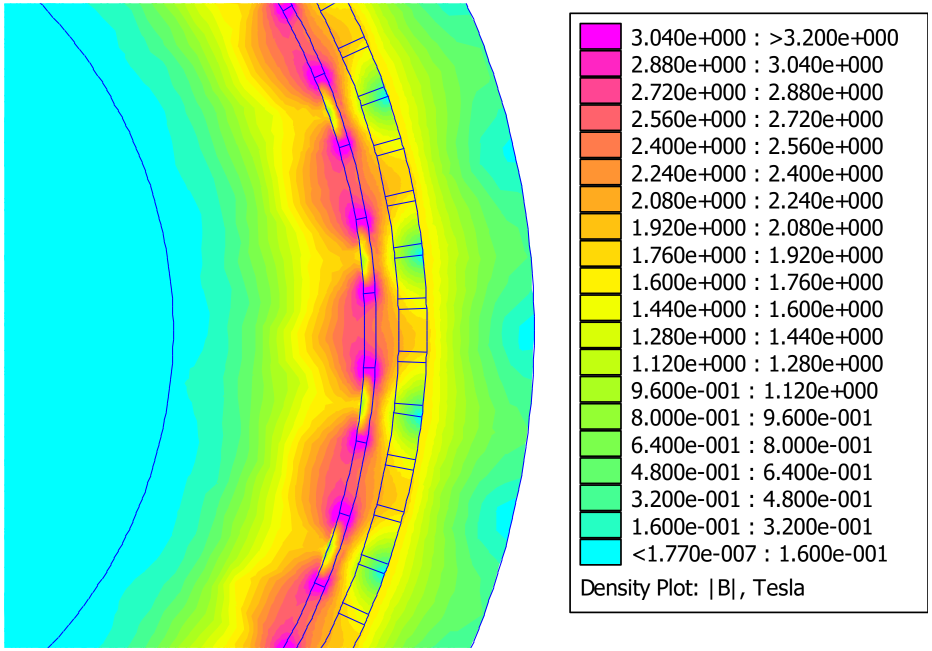
- The analytical model allows fast computations: the cpu time is around 5 minutes ; the convergence of the algorithm is obtained after 1000-1500 iterations.
- For the sizing, the torque value has been increased by 20% to allow for stability during transients and to consider saturation not taken into account by the analytical model.
- The rotor current density Jr cannot exceed 90% of the operating current determined by the load line method
- The optimum is obtained for 14 pole-pairs which results in operating frequency of **1,166 kHz** (Litz wires may be necessary for the armature winding).
- An active power density of about 26 kW/kg is achieved which is 30% higher than state of the art oil-cooled radial field PMSM.

Name	Value
Number of pole pairs	14
External diameter	59 cm
Active length	58 mm
Airgap (including cryostat)	8 mm
Stator winding (Copper) thickness	10 mm
Rotor HTS (YBCO) winding thickness	4 mm
Stator back-iron (FeCo) thickness	38 mm
Rotor back-iron (FeCo) thickness	68 mm
Stator slot width / tooth pitch ratio	0.8
Rotor slot width / pole pitch ratio	0.5
Stator slot rms current density	15 A/mm²
Rotor HTS winding dc current density	793 A/mm²
Maximal perpendicular flux density on HTS winding	3 T
Active mass	76.5 kg

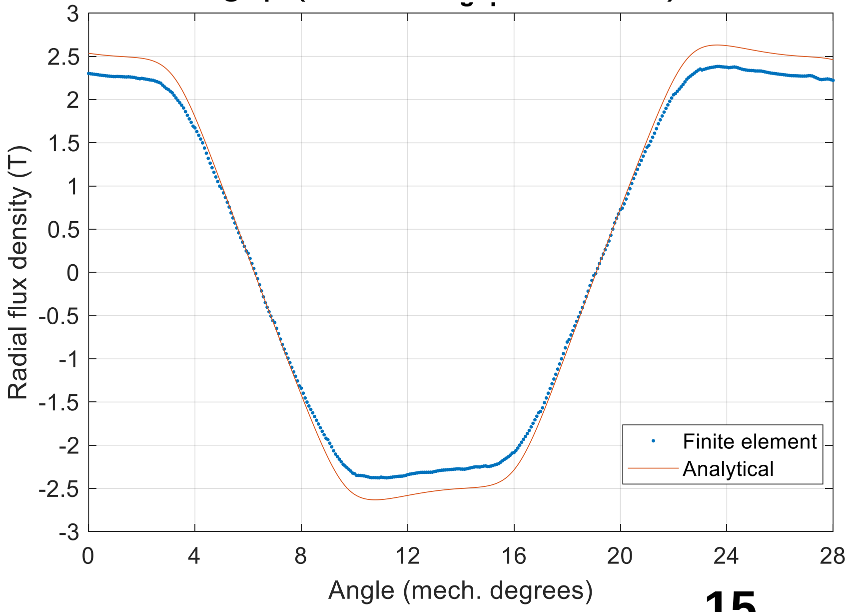
Sizing a 2 MW - 5000 rpm HTS machine

Finite element validation

- Cobalt iron laminations are used which allows high saturation level (in excess of 2,4 T)
- The analytical model doesn't consider saturation so the max flux density in the HTS winding is limited to 3 T
- The analytical and FE results are in good accordance
- The torque difference doesn't exceed 10%



Radial flux density distribution in the middle of the airgap (full load, saturated FE)



Conclusions

- HTS synchronous machine is sized via a combination of analytical model and optimization algorithm
- The computation tool is a free spreadsheet software which can easily
- 2D analytical models, validated by finite elements, for sizing and optimizing HTS machines taken into account the operating current of HTS coils
- Investigation of iron free machines are currently considered to reduce weight owing the high performances of the 2G tapes, in particular at higher flux densities.

THANK YOU FOR YOUR ATTENTION

Any question? Contact:

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