Study of AC losses in HTS tapes coupling FEM and electrical circuits with harmonics

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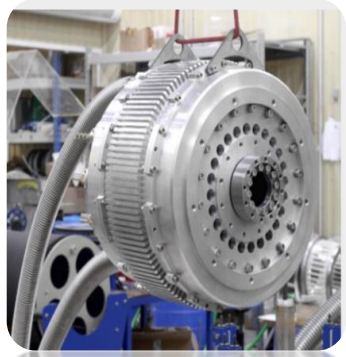
Context of the work

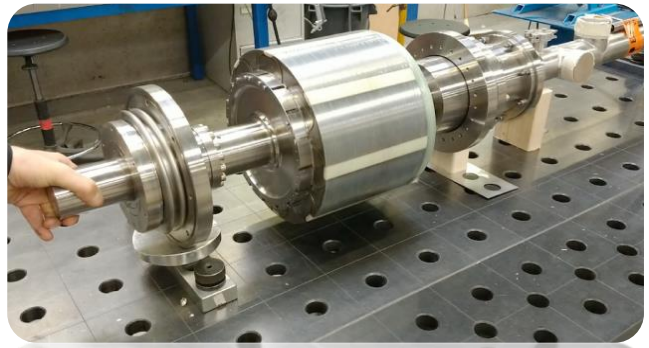
Projects

Machine Projects



Flight test on a Yak-40 (SuperOx)

Axial flux modulation machine 50 kW (GREEN)



Experimental Motor Demonstrator (ASuMED)

Cable Projects

LIPA 138 kV, 2.4 kA (Nexans)

13.2 kV, 3 kA, 200 m (Ultera)

22.9 kV, 50 MVA, 100 m (LS Cable)

Modelling tools

- ✓ **H** formulation 2D – 3D
- ✓ **H** – φ formulation 2D – 3D
- ✓ **H** – **A** formulation 2D – 3D
- ✓ **T** – **A** formulation 2D – 3D

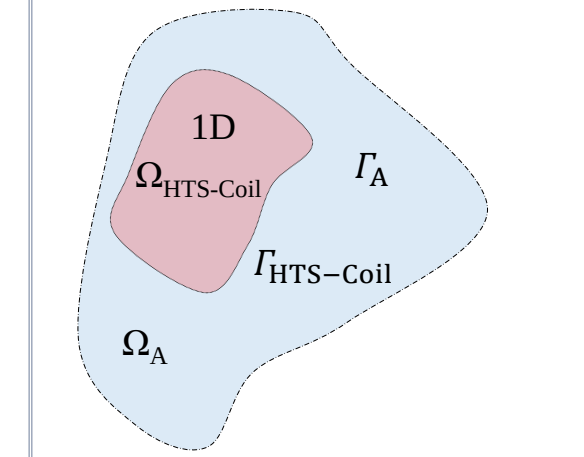
What's next?

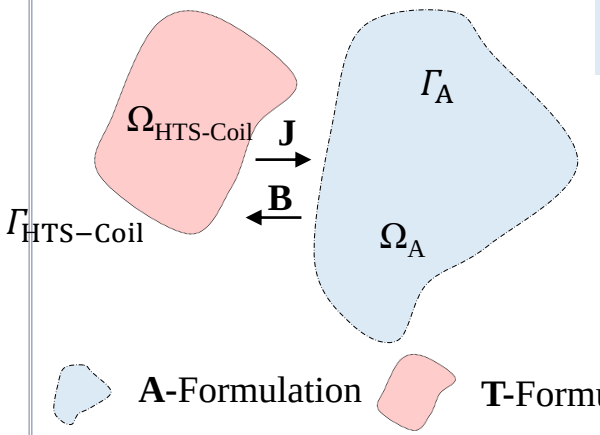
More complex/realistic electrical network coupled with FEM

Presentation Outline

- Modelling framework
- Circuit coupling with Simulink and COMSOL
  - ❖ LiveLink™ for Simulink®
- Two case studies and two HTS samples
  - ❖ pure sine wave and half-wave rectified signal
  - ❖ a single tape and a coil
- Test bench and sample presentation
- Validation of the co-simulation
  - ❖AC losses of a single tape with pure sine
- More results with an HTS coil

In brief : **T-A** Formulation





A-Formulation **T**-Formulation

T-Formulation

$$\nabla \times (\rho \nabla \times \mathbf{T}) = -\frac{d\mathbf{B}}{dt}$$

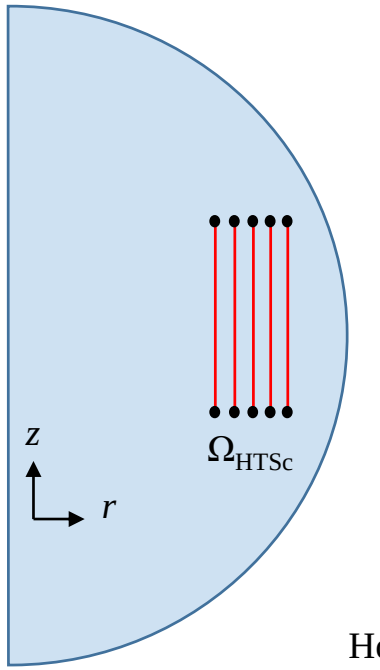
$\mathbf{J} = \nabla \times \mathbf{T}$

B ↑ J ↓

A-Formulation

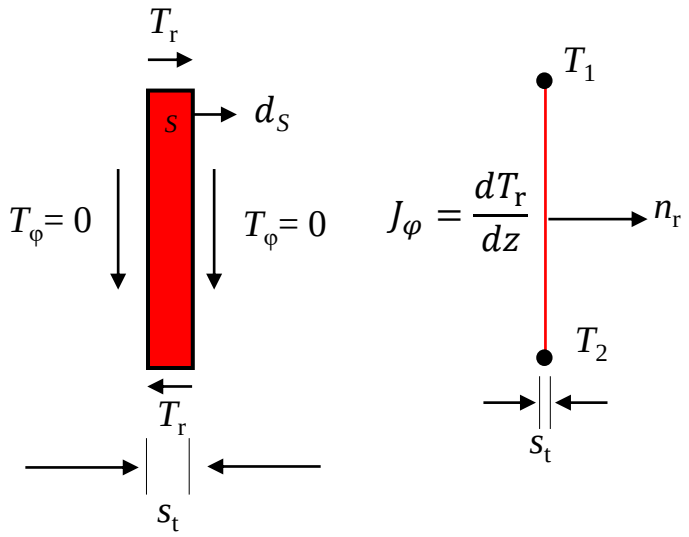
$$\nabla \times \left(\frac{1}{\mu_0} \nabla \times \mathbf{A}\right) = 0$$

$\mathbf{B} = \nabla \times \mathbf{A}$



Symmetry axis

- Dirichlet Boundary Condition



How to impose the current? $I = (T_1 - T_2) / \delta$

E(J) Law :

$$\rho_{\text{HTSc}} = \frac{E_{\text{c}}}{J_{\text{c,HTSc}}} \left(\frac{J_{\text{HTSc}}}{J_{\text{c,HTSc}}(B,T)}\right)^{n_{\text{HTSc}}(B,T)}$$

Kim model:

$$J_{\text{c,HTSc}}(B_\parallel, B_\perp) = \frac{J_{\text{c0,HTSc}}}{\left(1 + \frac{\sqrt{k_{\text{a}}^2 B_\parallel^2 + B_\perp^2}}{B_0}\right)^\beta}$$

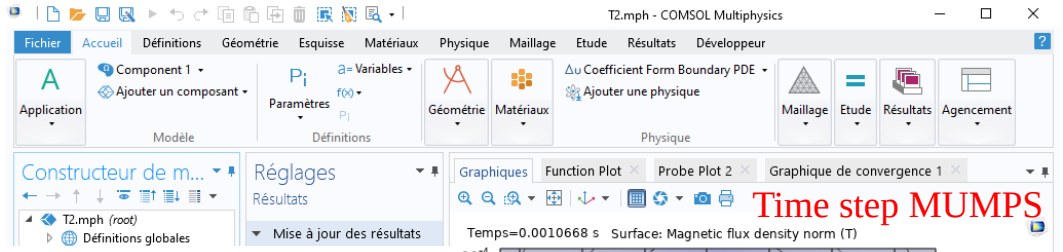
Circuit coupling and FEM (LiveLink™ for Simulink® since 2020)

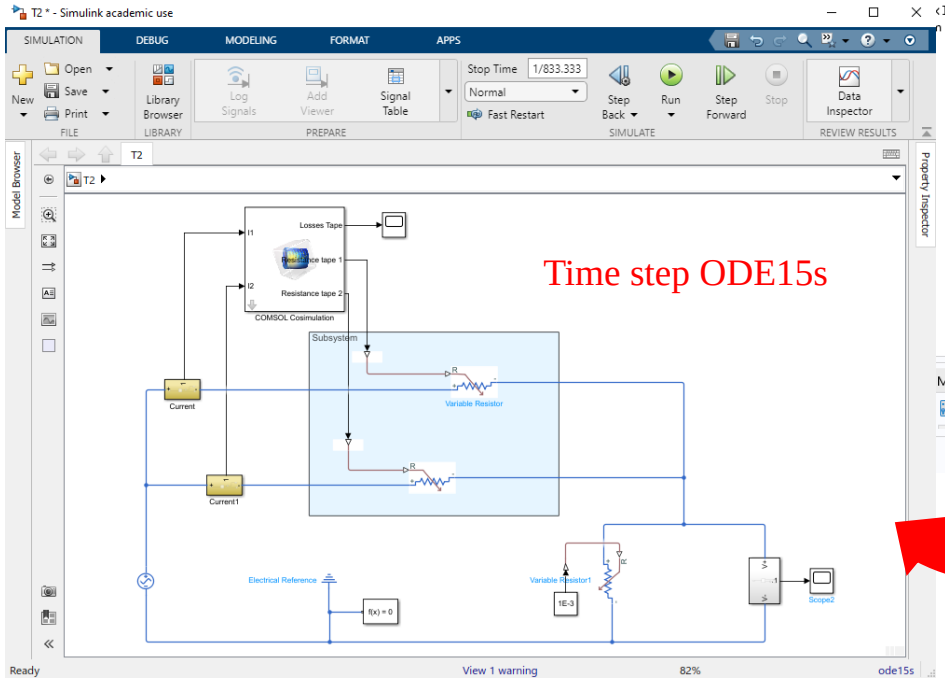
SIMULINK

Driving global variables with the **ODE15s** solver

COMSOL

Control of local and global variables with a **local MUMPS** solver





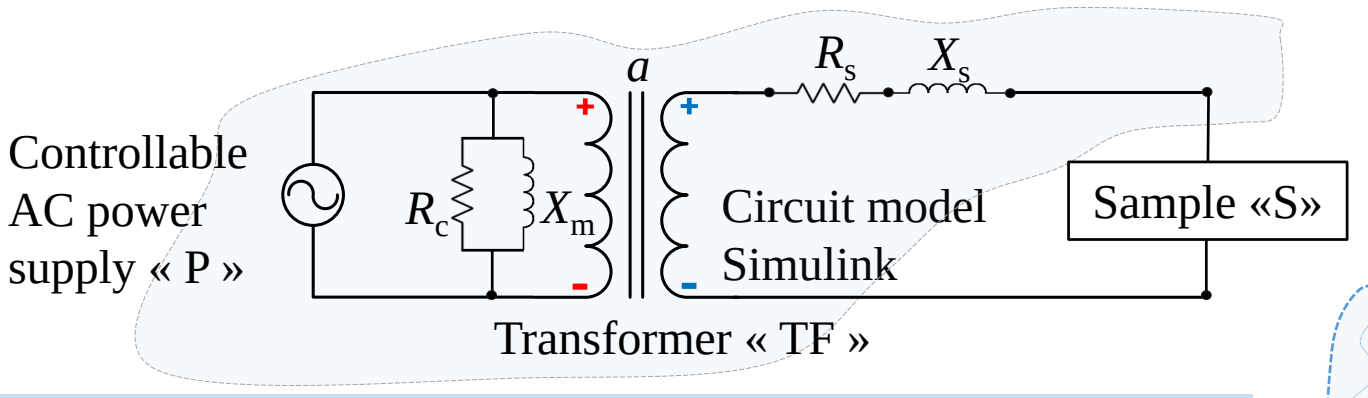
Preliminary objective:
To study the impact of different time steps on **convergence**, **accuracy** and **computation time**.

Final objective: to study the impact **of network harmonics** on the superconducting materials.

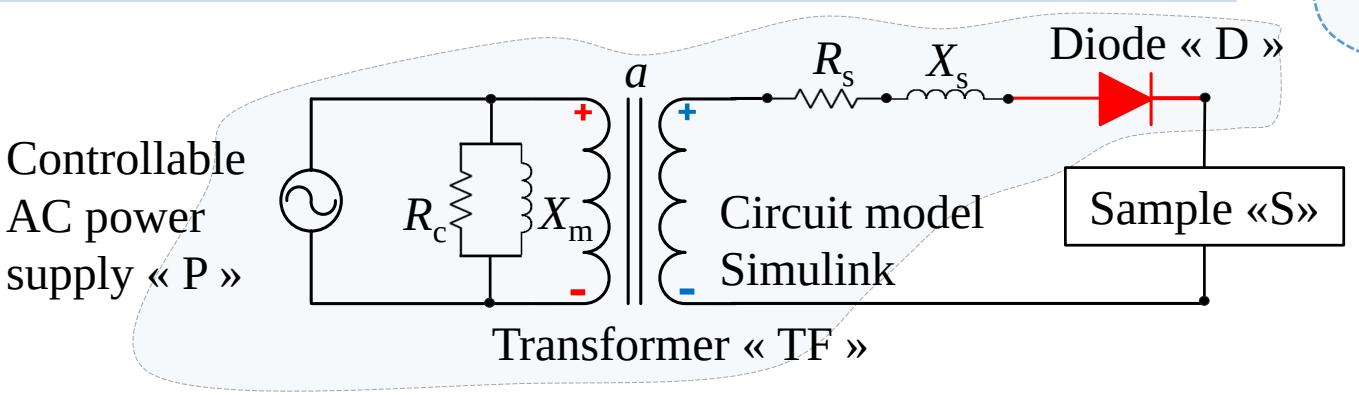
Communication step:
the interval from t to $t + dt$ that is simulated in COMSOL at the communication time t.

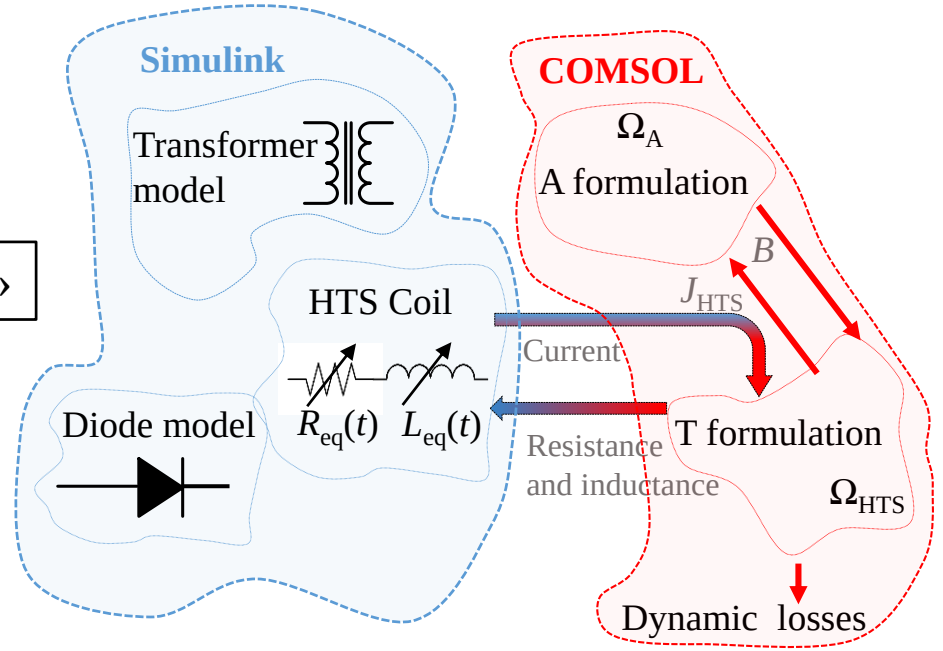
Two case studies

1) Pure sinusoidal signal



2) Half-wave rectified signal using a Diode





Communication at each time step of ODE15s

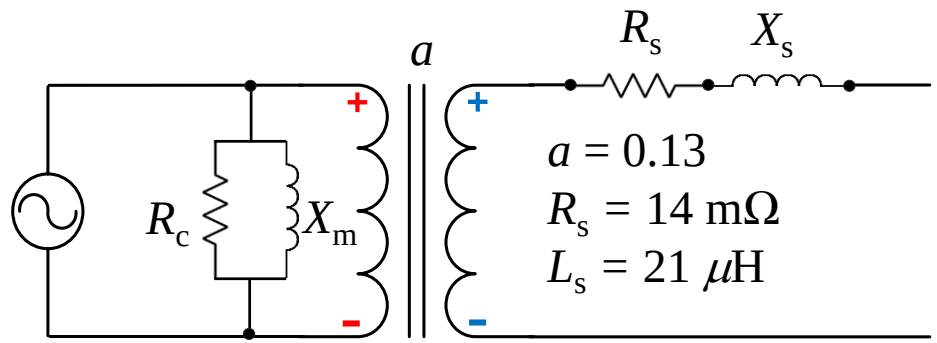
Communication at each coupling time step

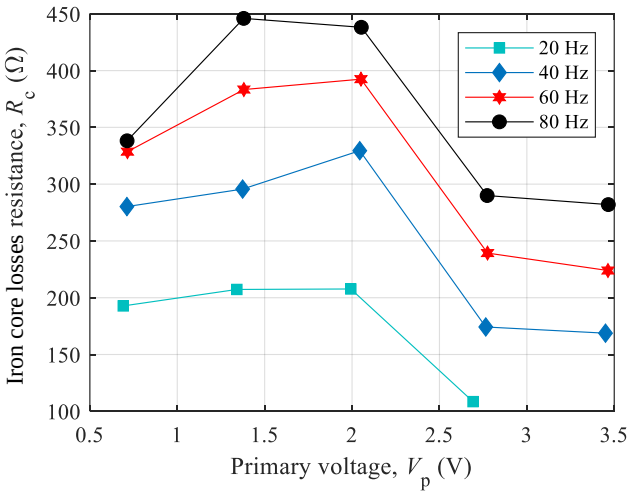
Communication at each time step of MUMPS

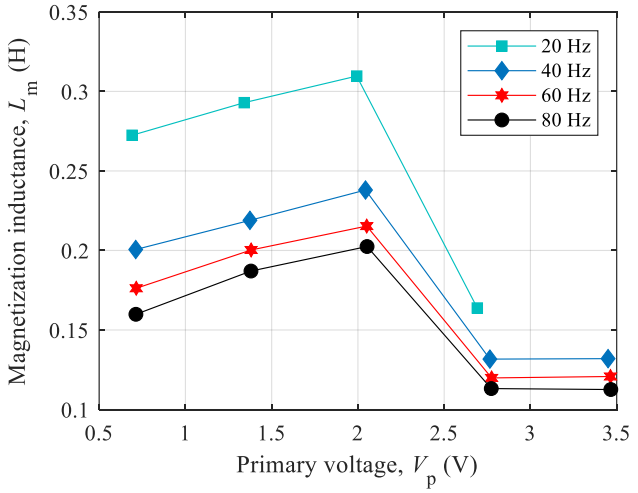
Test bench

Controllable AC power supply « P »

Identifying the parameters of the step-down transformer immersed in liquid nitrogen



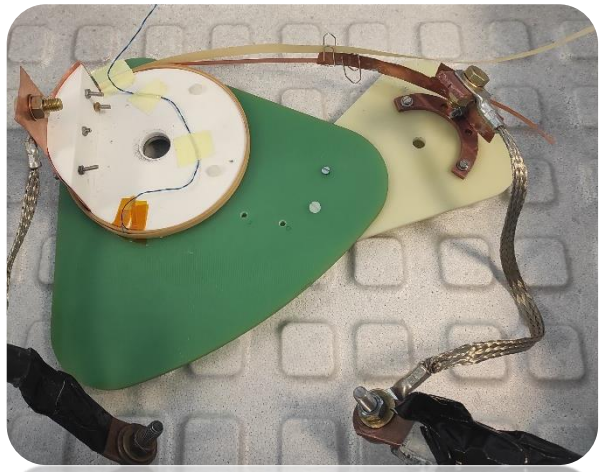




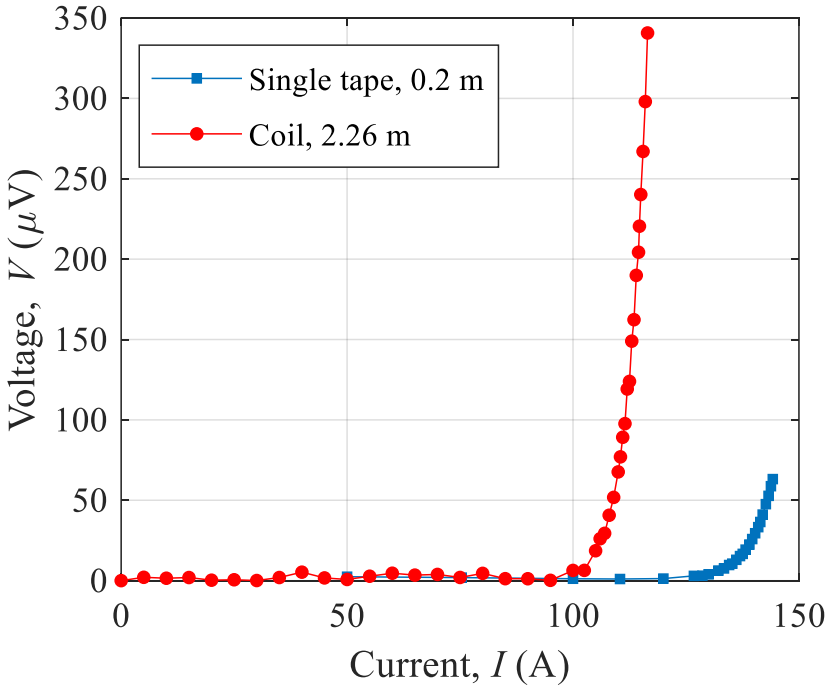
HTS samples: a single tape and a coil

Both samples are made with tapes manufactured by: **Shanghai Superconductor Technology**

Single HTS 2G tape
Length: 0.20 m
Width: 4 mm
I_c = 138.5 A
n = 22



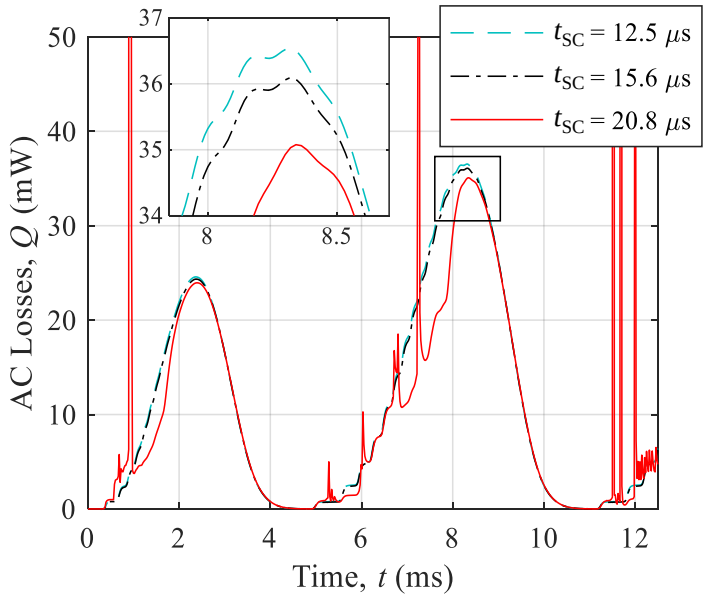
2G HTS Coil:
Length: 2.26 m
Diameter: 120 mm
number of turns: 6
I_c=114.5 A
n = 22

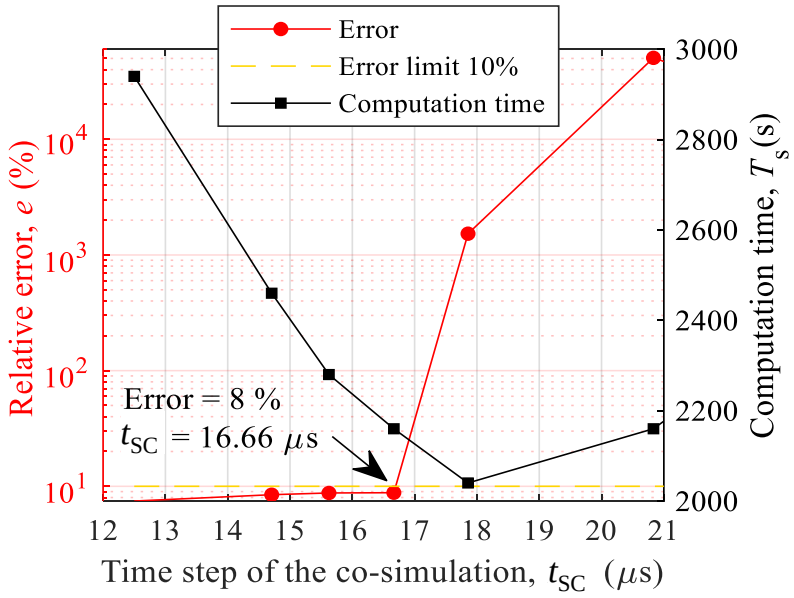


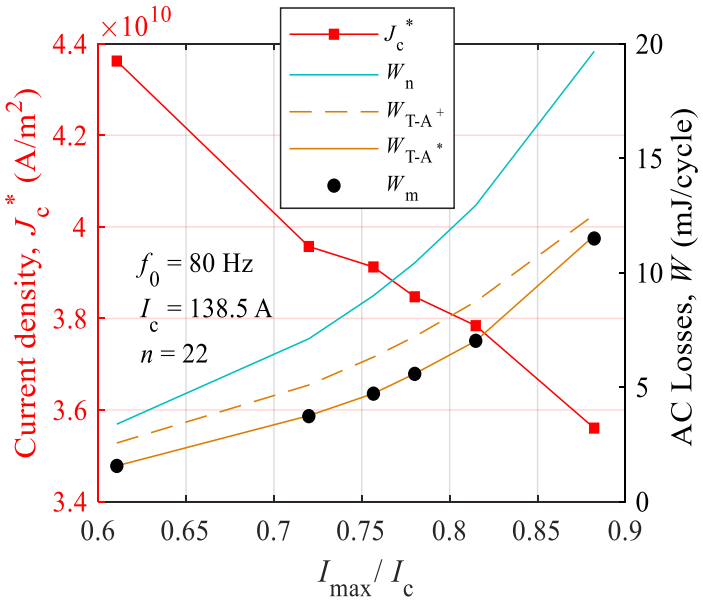
AC losses calculation of a single tape @80Hz

The different time steps:

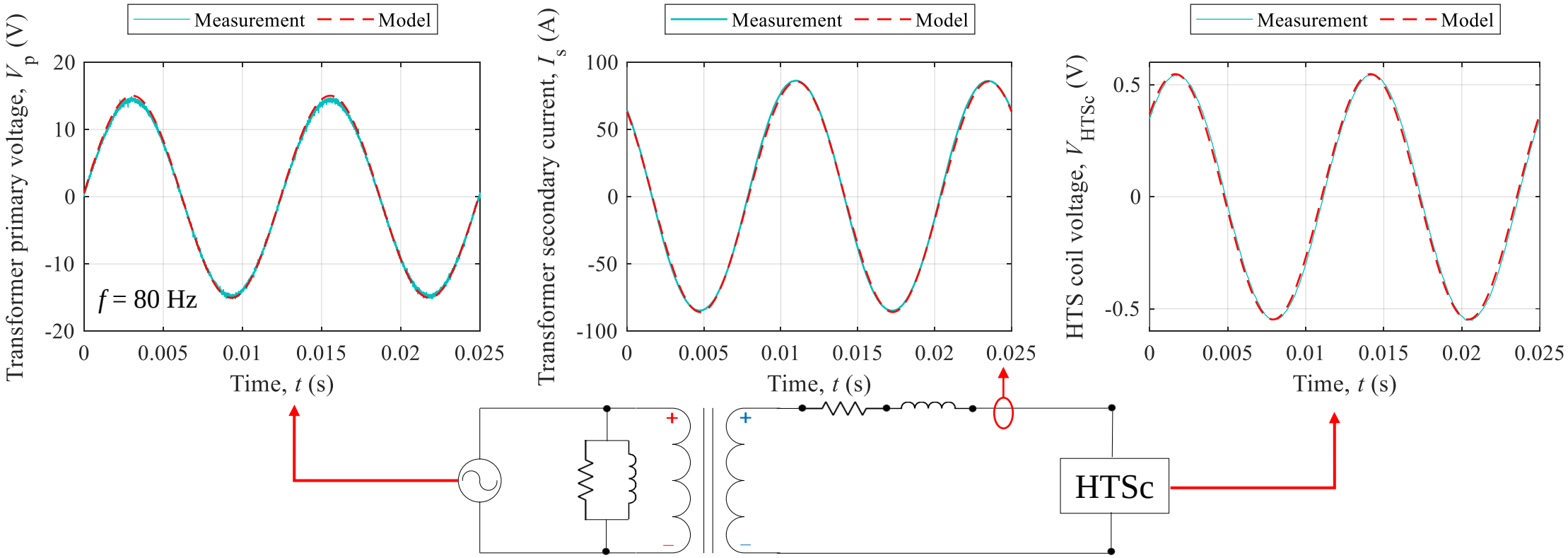
- Maximum time step in Simulink (**ODE15** solver) : $t_{Smax} = T / 1000 = 12.5\ \mu s$
- Maximum time step in COMSOL (**MUMPS** solver) : $t_{Cmax} = T / 1000$
- Communication time step between the two softwares : $T / 500 < t_{SC} < T / 1000$





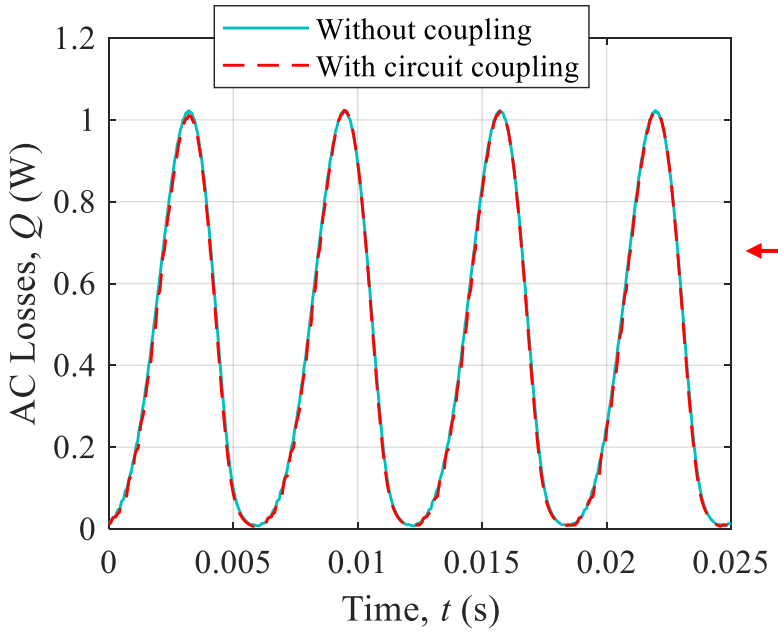


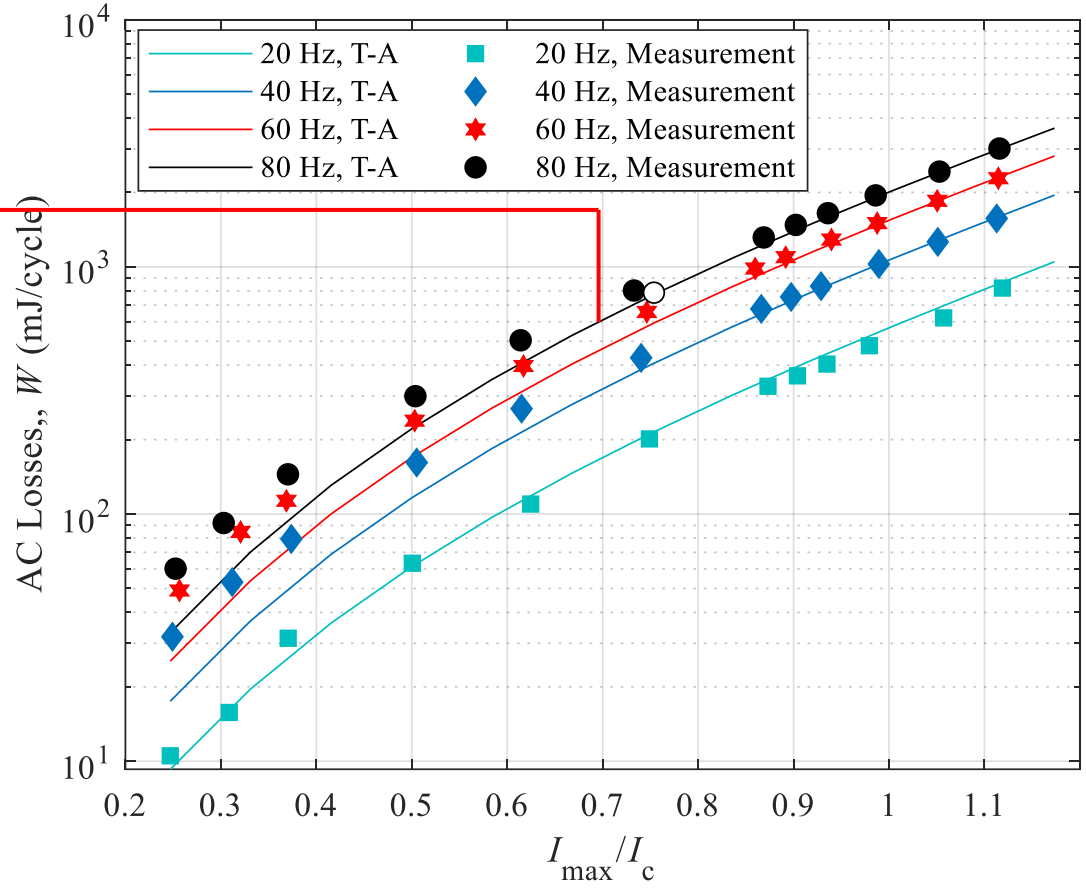
Electrical model validation with coil



- Maximum time step in Simulink (**ODE15** solver) : $t_S = T / 1000 = 12.5\ \mu s$
- Maximum time step in COMSOL (**MUMPS** solver) : $t_C = T / 1000$

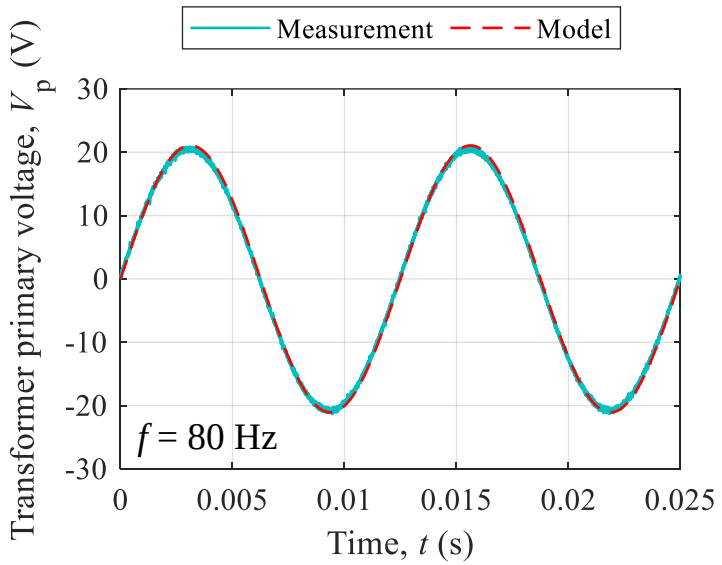
AC Losses for an HTS Coil in pure sine

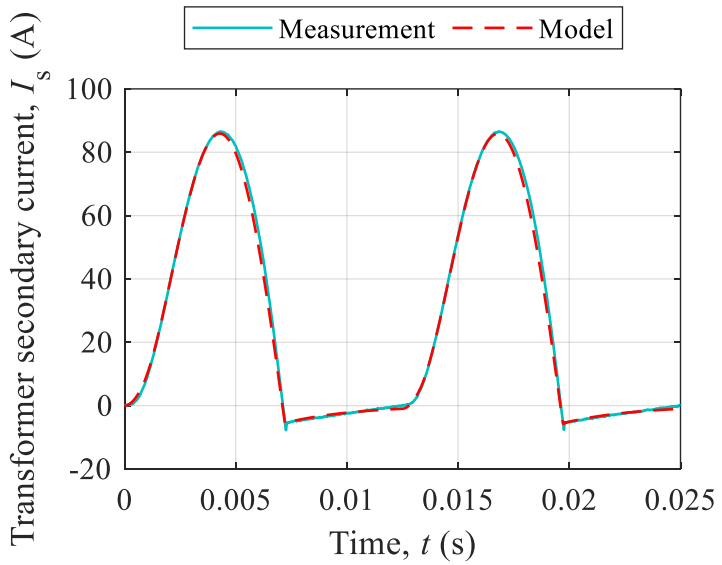


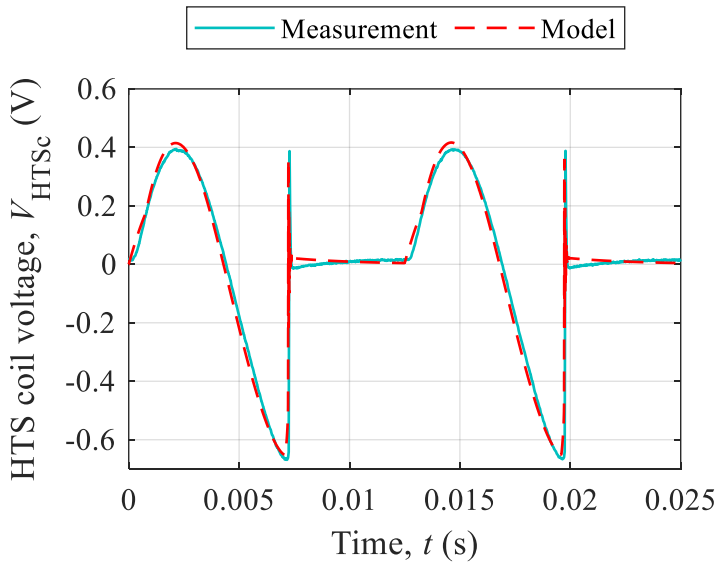


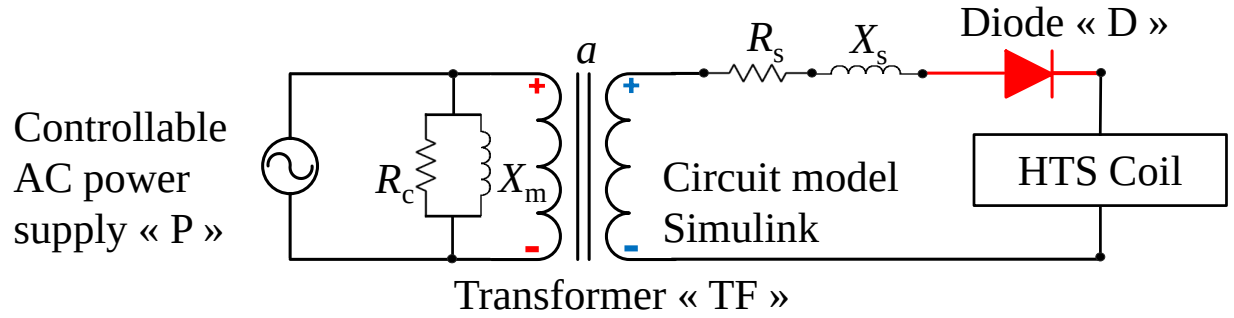
- Calculation Time **12 h 20 min!**
- Temporary storage of **810 GB** for a communication time step between the two programs of **12.5 µs and for 3 cycles**

HTS Coil with half-wave rectified signal

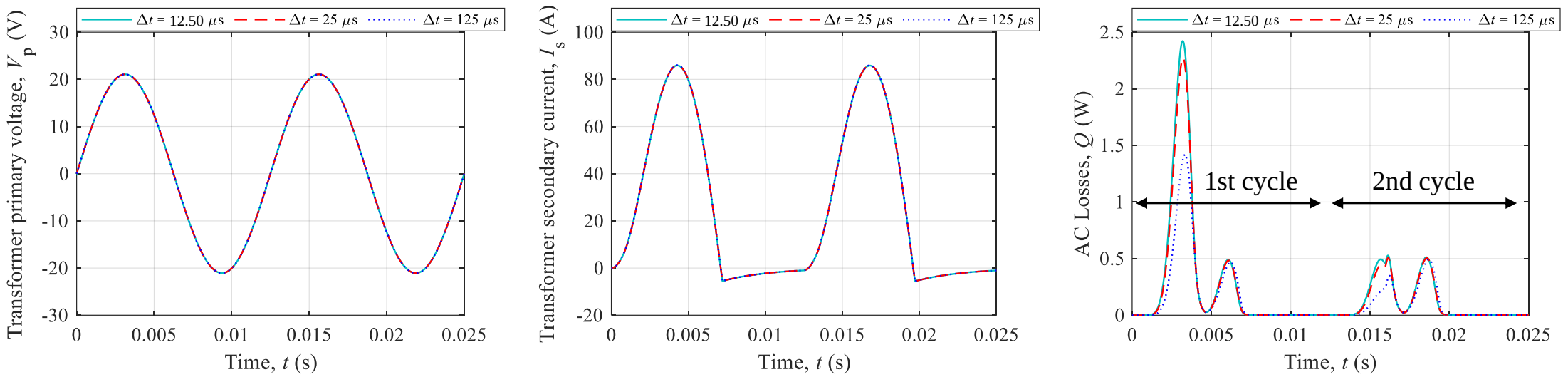








Influence of the communication step



- Communication time step between the two softwares : $\boldsymbol{T / 100 < t_{SC} < T / 1000}$
- The communication step between the two software has little influence for superconducting applications
  In general, the impedance of superconducting materials is very low compared to the impedance of the electrical network.

Tips to remember

- Coupling processes

  https://www.comsol.fr/livelink-for-simulink

- Approach and tips for convergence problems related to superconductor nonlinearity.

Step 1: check that each model works separately

Variable time step
Ode15s, Ode23t ...
Set the maximum time step: 1 / f / n_S

Constant time step
Ode1(Euler), Ode3(Bogacji-Shampine),...
Set the time step :1 / f / n_S

Step 2: n_S is chosen so that the results of Simulink alone are accurate

Step 3: Do the same in COMSOL, it is recommended that n_C be **identical within Simulink n_S.**

Step 4: The communication step between the two programs n_{CS} must be in the range **$0.75\ n_S < n_{CS} < n_S$**

Execute and enjoy!

Conclusion

- Co-simulation with LiveLink for Simulink currently shows some limitations in terms of
  - computation time
  - buffer storage
- In some cases the AC losses can be estimated with a higher accuracy by strongly lowering the communication step
- Very particular phenomena can be simulated by including the real behavior of the electrical components, especially the switching ones
  - extraction of charge carriers
  - overvoltage…
- Results are encouraging and we can still consider the simulation of complex superconducting systems
  - See next presentation of Frederic Trillaud

Thank you for your attention

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