Fast Modeling Approach for Computing AC Losses in HTS Stacks and Coils Near Ferromagnetic Parts

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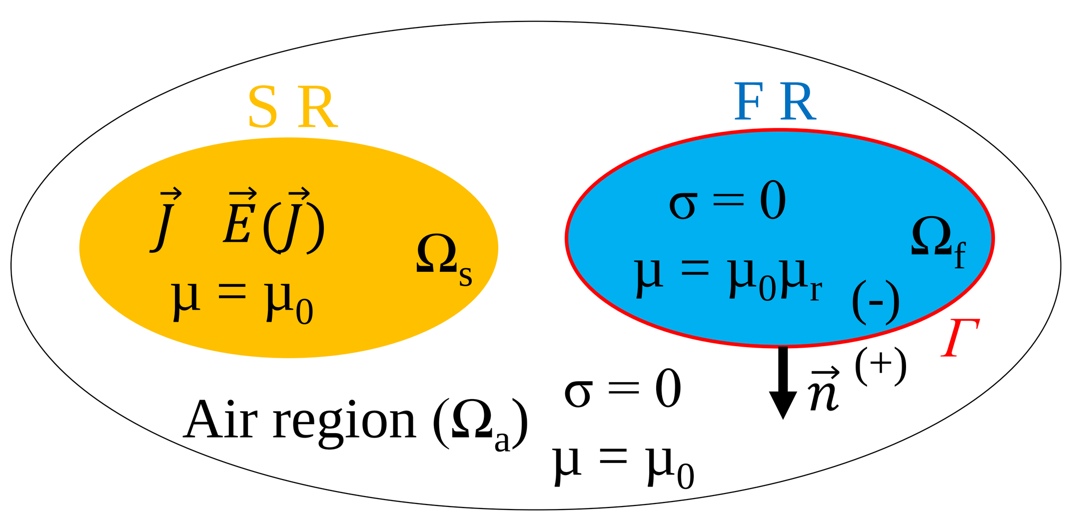
Abstract

This work presents a fast integral modeling approach for computing AC loss in high temperature superconducting (HTS) tapes and stacks. The A-V formulation is combined with the equivalent current model to take into account of the proximity of ferromagnetic materials with finite relative permeability [1]. The obtained results are compared with finite element analysis, both on local and global quantities.

The modeling approach

The modeled system



Superconducting region (S R)

$$\begin{cases} E(J,B) = E_c \left|J_c^{-1}(B)\,J\right|^n \\ J_c(B) = \dfrac{J_{c0}}{\left(1+B_0^{-1}\sqrt{\alpha^2|B_x|^2+|B_y|^2}\right)^{\beta}} \end{cases}$$

Ferromagnetic region (F R)

$$\vec B = \mu_0\mu_r\vec H = \mu_0\left(\vec H + \vec M\right)$$

$$\vec M = \frac{(\mu_r-1)}{\mu_0\mu_r}\vec B$$

Equivalent surface current density : $\vec k$

$$\vec k(\vec r) = \vec M\times\vec n = \frac{(\mu_r-1)}{\mu_0\mu_r}\vec B(\vec r\in\Gamma^{(-)})\times\vec n$$ With: $$\vec B(\vec r) = \vec B_{\vec J}(\vec r) + \vec B_{\vec k}(\vec r)$$

When $\vec r\in\Gamma$, we have: $$\vec B(\vec r\in\Gamma^{(\pm)})\times\vec n = \mp\frac{\mu_0}{2}\vec k(\vec r) + \left[\vec B_{\vec k(\vec r'\neq\vec r)}(\vec r) + \vec B_{\vec J}(\vec r)\right]\times\vec n$$

The jump of $\vec B$ across Γ is: $$\left[\vec B(\vec r\in\Gamma^{(+)}) - \vec B(\vec r\in\Gamma^{(-)})\right]\times\vec n = -\mu_0\vec k(\vec r)$$

The final relation between $\vec k$ & $\vec J$ is: $$\vec k(\vec r) = \frac{2(\mu_r-1)}{\mu_0(\mu_r+1)}\left[\vec B_{\vec k(\vec r'\neq\vec r)}(\vec r) - \vec B_{\vec J}(\vec r)\right]\times\vec n$$

The matrix form of $\vec k$ is then: $$\left\{\overline{\overline{I}} + \overline{\overline{M}}_{FF}\right\}\overline{k} = \overline{\overline{M}}_{FS}\,\overline{J} \Rightarrow \overline{k} = \left\{\overline{\overline{I}} + \overline{\overline{M}}_{FF}\right\}^{-1}\overline{\overline{M}}_{FS}\,\overline{J}$$

Formulation

From the Maxwell's equations, we have : $\partial_t\vec A + \vec E + \vec\nabla V = \vec 0$

With: $$\overline{A} = \overline{A}_J + \overline{A}_k = \overline{\overline{L}}_{SS}\,\overline{J} + \overline{\overline{L}}_{SF}\left(\overline{\overline{I}} + \overline{\overline{M}}_{FF}\right)^{-1}\overline{\overline{M}}_{FS}\,\overline{J}$$

We have to solve: $$\left[\overline{\overline{L}}_{SF}\left(\overline{\overline{I}} + \overline{\overline{M}}_{FF}\right)^{-1}\overline{\overline{M}}_{FS} + \overline{\overline{L}}_{SS}\right]\partial_t\overline{J} + \overline{E} + \overline{\nabla V} = \overline{0}$$

Results and Comparisons

The used parameters: A sinusoidal current of amplitude (I_{app}) was applied

Parameter	J_{c0}	α	B_0	β	n	f	a	h_Y	h_S	h_C	μ_r	n_t	n_l	w
Value	28 GA/m²	0.29515	42,65 mT	0.7	38	50 Hz	4 mm	1 µm	50 µm	293 µm	100	32	18	$n_t \times h_C$

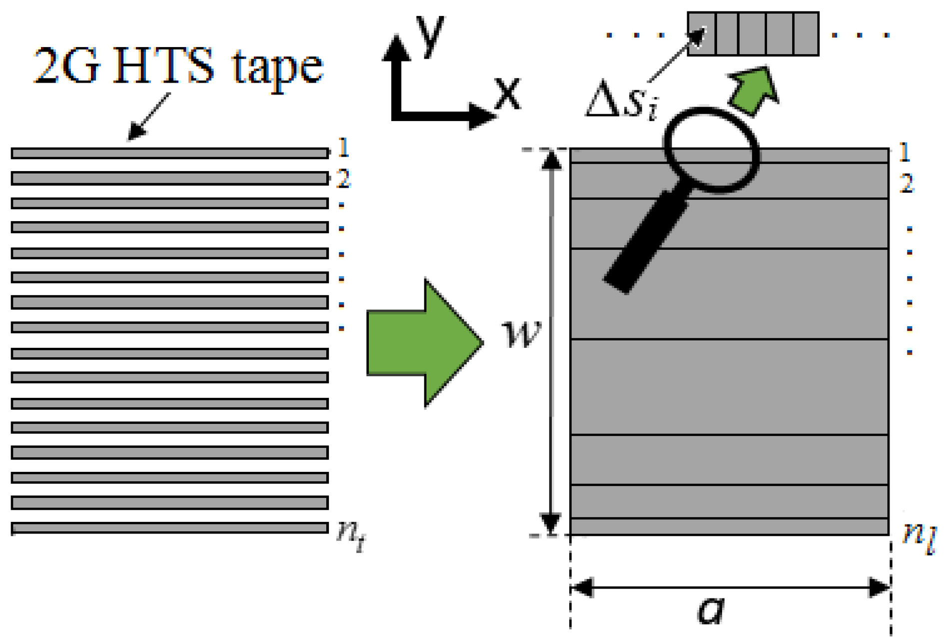
2G HTS stack

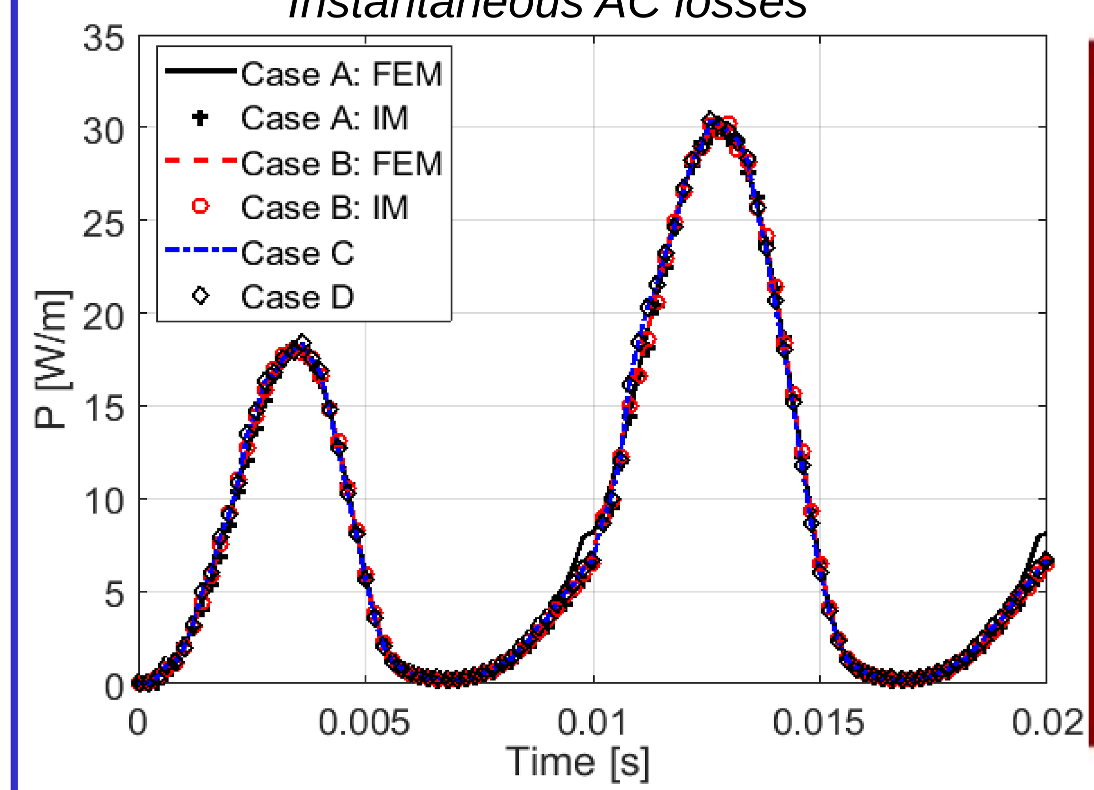
Case A: Original stack.

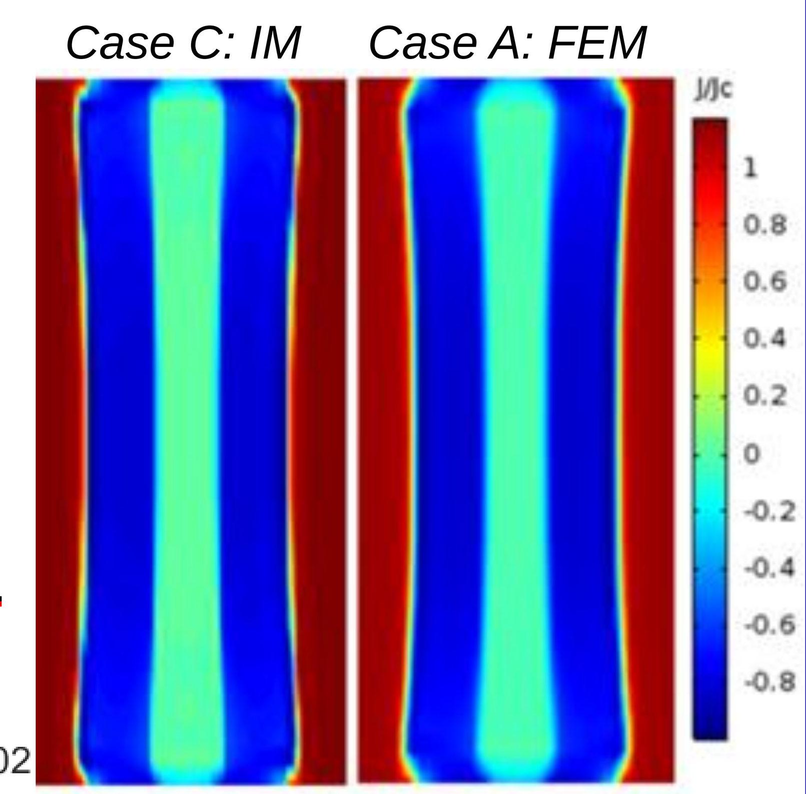
Case B: Homogenized stack.

Case C: Homogenized stack, reducing the integral matrices by using the fast multipole method (FMM).

Case D: The same as in **Case C** where the losses are evaluated only on the half of the layers, skipping one layer between two layers. An interpolation method is then used to predict the losses on the skipped layers.







Average AC loss (W/m) / Computing time (in seconds)

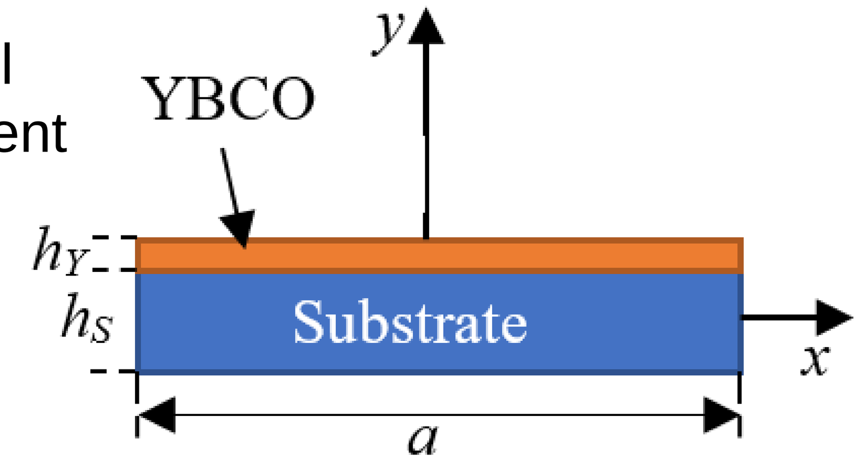
I_{app}	Model	Case A		Case B		Case C		Case D	
60 A	IM	11,23	607	11.30	208	11.38	64	11.41	32
	FEM	11.42	3478	11.40	449	/		/	

Benchmark # 02 : 2G HTS tape with ferromagnetic substrate

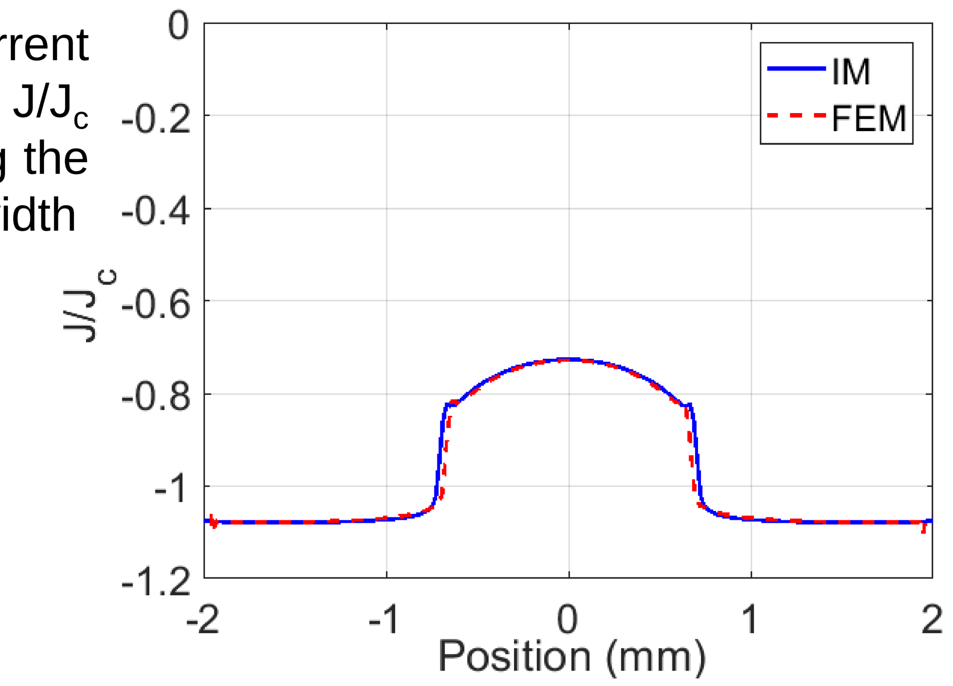
IM: Integral model

FEM: Finite element method

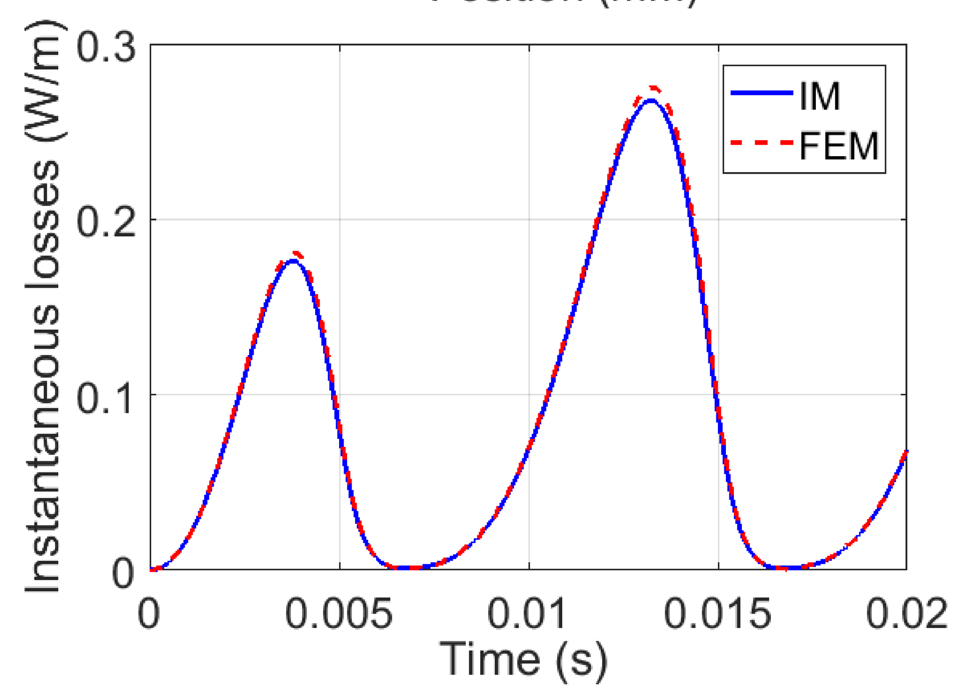
I_{app} = 90 A



Normalized current density profiles J/J$_c$ at t=3/(4f) along the YBCO layer's width



Instantaneous AC losses



[1] Y. Statra, H. Menana and B. Douine, «*Semianalytical Modeling of AC Losses in HTS Stacks Near Ferromagnetic Parts*», *IEEE Trans. Appl. Supercond.*, vol. 31, no. 1, pp. 1-6, 2021.