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

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***Abstract*—This paper presents a fast modelling approach for computing AC loss in high temperature superconducting (HTS) stacks and coils. The Brandt's model is extended for large scale systems, taking into account the presence of ferromagnetic parts. The obtained results are compared with finite element analysis, both on local and global quantities.**

Keywords—Modelling, AC loss, Volume integral equations, HTS stacks and coils, ferromagnetic parts.

I. INTRODUCTION

The development of high temperature superconductor (HTS) materials allows to achieve some practicable power applications, such as: motors, fault current limiter and superconducting magnetic energy storage systems. To ensure safe operation of these devices, their design should consider the evaluation of AC losses. Indeed, even if HTS materials do not show significant losses at DC regimes, they present important AC losses, both on self (transport current) and applied time varying magnetic fields.

AC loss can be evaluated by analytical formulas based on the critical state model, for very simple structures [1]. Numerical methods, such as the finite element method (FEM), are generally used with the power law relating the electrical field to the current density, taking into account the dependence of the critical current density on the magnetic field [2]. However, they are generally time consuming. Semi-analytical methods, such as the Brandt's method [3], based on volume integral equations, present a very good compromise between accuracy and computation time. These methods limit the discretization to the active parts of the modelled system, and do not require boundary conditions. They are widely used to evaluate induced currents and ac losses in thin strips, rectangular wires, and cylindrical bulks [4]. However, for large scale systems, they remain time consuming, due to the full integral matrices resulting from the problem discretization.

In this work, the Brandt's method is extended to model large scale stacks and pancake coils, taking into account the presence of ferromagnetic parts. Different discretization strategies are considered. The ferromagnetic parts are taken into account by using the method of images. A comparison with a FEM analysis, in terms of accuracy and computation times, is performed.

II. THE MODELLIG APPROACH

The modelling approach is illustrated on the HTS system shown in fig.1-a. It consists on a vertical stack of 2G HTS tapes, placed near a ferromagnetic part. The stack is treated as a homogenized anisotropic bulk (Fig.2-b) [2]. The discretization along the y direction is not constrained to the number of tapes, and it is optimized to discretize finely only the parts where the field varies significantly. The homogenized HTS bulk is discretized into n_c layers (C_i, i=1,2, ..., n_c) along the y direction, and into N_x elements along the x direction numbered i $(i=1,\dots, N_x)$, carrying a uniform current density J_i.

Firstly, only the HTS stack is treated (without iron part). The magnetic vector potential *(A)* and the magnetic field *(B)* can be calculated by the Biot and Savart formulas, leading to the following expressions:

$$\left\{ A_{z,i} = \sum_{j=1}^{N} K_{ij} J_j ;\;\; B_{x,i} = \sum_{j=1}^{N} L_{ij} J_j ;\;\; B_{y,i} = \sum_{j=1}^{N} M_{ij} J_j \right\} \quad (1)$$

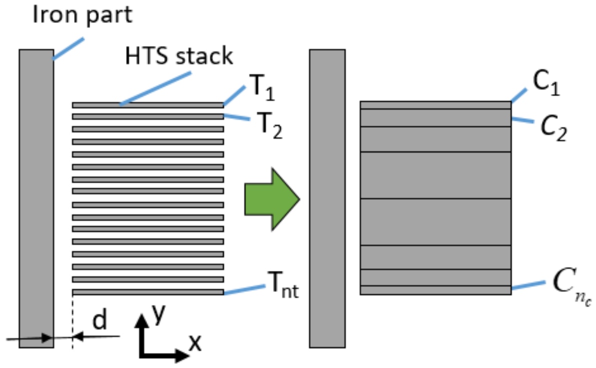
where K, L and M are matrix of size $(N\times N)$, where $N=N_x\times n_c$.

From the Maxwell's equations, and by using the power law to express the electric field *(E)*, the following equation is derived, where φ, E_c and J_c are respectively the electric scalar potential, the critical electric field and the critical current density of the HTS.

$$\sum_{j=1}^{N} K_{ij} \partial_t J_j = -\left[E_c \left(J_i / (J_c)_i \right)^n + (\nabla\phi)_i \right] \quad (2)$$

If a transport current is applied, the gradient of the scalar potential can be calculated by using (3) [4], where γ is a feedback constant, $J_{set}\,(t)$ is the desired current density, and S is a matrix which contains square sub-matrices in its diagonal. Each sub-matrix corresponds to the surface elements of each layer.

$$(\nabla\phi)_i = \gamma \sum_{j=1}^{N} S_{ij} \left(J_j - J_{set}(t) \right) \quad (3)$$



(a) (b)

Fig. 1. The modelled system.

The Kim's model is used to take into account the $J_c(B)$ dependence, given in (4) [5], where f_{HTS} is the volume fraction of the superconducting material.

$$J_{c,i}(B) = J_{c_0} f_{HTS} \left(1 + B_0^{-1}\sqrt{k^2\left|B_{y,i}\right|^2 + \left|B_{x,i}\right|^2}\right)^{-\beta} \quad (4)$$

We tested three strategies to evaluate the AC losses:

<u>Case A:</u> Homogenized stack.

<u>Case B:</u> Homogenized stack, reducing the integral matrices by using the fast multipole method (FMM).

<u>Case C:</u> Homogenized stack, where the losses are evaluated only on the half of the layers (C_{2k+1}, k=0,…, round((n_c-1)/2)), skipping one layer between two layers where the losses are evaluated. An interpolation method is then used to predict the losses on the skipped layers.

Finally, the iron part is included in the modeling by using the images method.

III. Results and Discussions

To check the validity and performance of the modeling approaches, the results are compared to finite element analysis using H-formulation [2]. The values of parameters used in the simulation are given in table I. Stacks of 16, 32, and 64 tapes were considered. The amplitudes of the applied sinusoidal currents were 70 A, 60 A, and 50 A for the stacks of 16, 32, and 64 tapes, respectively.

TABLE I. Parameter values used for simulations

Parameter	*Value*	*Description*
hHTS	1 µm	YBCO layer thickness
hTape	93 µm	Tape thickness
hCell	293 µm	Unit cell thickness (Tape+air)
a	4 mm	Tape width
n_t	16 - 32 - 64	Number of tapes in the stack
E_c	1 µV/cm	Critical electric field
n	38	Power law exponent
J_{c0}	28 GA/m^2	Critical current density
n_c	18	Number of layers
N_x	50	Number of elements along x
f	50 Hz	Frequency of the applied current
γ	100	feedback constant
k	0.29515	Constant used in (4)
B_0	42,65 mT	Constant used in (4)
β	0.7	Constant used in (4)
d	1 mm	Stack-Iron part separation distance

Figure 2 shows a comparison between the modeling approach (case B) and the FEM analysis on the repartition of the normalized electric current density (J/J_c), with and without the iron part, for a stack composed of 32 tapes at $t=1/f$. As it can be noticed, a similar repartition of the electric current density is obtained.

Table II present the average AC losses calculated with the three strategies, compared to the results given in [2]. A good agreement is found between the results, for all the cases considered. A good agreement was also obtained for the instantaneous losses as shown in Fig.3.

Computing times are given in Table III. The speedup factor is improved by using the proposed strategies, compared to that obtained in [2].

More results considering the ferromagnetic part will be presented in the extended paper.

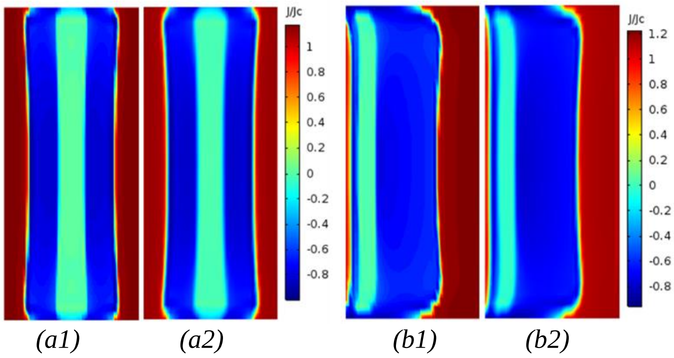


Fig. 2. Normalized current density J/J_c at $t=1/f$. (*a1*) Case B without iron, (*a2*) FEM without iron, (*b1*) Case B with iron, (*b2*) FEM with iron

TABLE II. Average AC loss in watts per meter / Erreur(%)

n_t	*Original Stack [2]*	*Homogenized Stack [2]*		*Case A*		*Case B*		*Case C*	
16	6.74	6.86	1.72	6.81	1.04	6.83	1.33	6.85	1.63
32	11.33	11.40	0.61	11.30	0.27	11.38	0.7	11.41	0.97
64	15.44	15.47	0.2	15.28	1.4	15.34	0.87	15.36	0.7

TABLE III. Computing time in seconds / Speedup factor

n_t	*Original Stack [2]*	*Homogenized Stack [2]*		*Case A*		*Case B*		*Case C*	
16	3251	639	5.09	215	14.8	69	47.16	36.4	89.3
32	8583	472	18.18	210	40.9	64	138.4	32	268.2
64	31206	426	73.25	196	159	54.5	572.6	27	1155.8

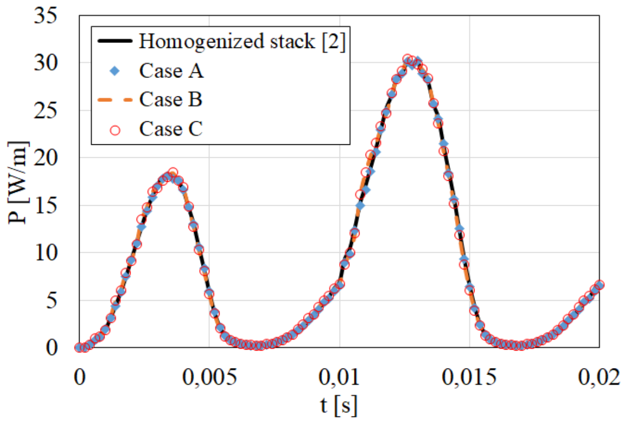


Fig. 3. Instantaneous losses for the stack of 32 tapes.

References

[1] W. T. Norris, "Calculation of hysteresis losses in hard superconductors carrying AC: Isolated conductors and edges of thin sheets," *J. Phys. D, Appl. Phys.*, vol. 3, no. 4, pp. 489–507, 1970.

[2] V. M. R. Zermeno, A. B. Abrahamsen, N. Mijatovic, B. B. Jensen and M P. Sørensen, "Calculation of alternating current losses in stacks and coils made of second generation high temperature superconducting tapes for large scale applications," J. Appl. Phys. 114 173901, 2013.

[3] E. H. Brandt, "Superconductors of finite thickness in a perpendicular magnetic field: Strips and slabs," *Phys. Rev. B*, vol. 54, no. 6, pp. 4246–4264,1996.

[4] S. Otten and F. Grilli, "Simple and Fast Method for Computing Induced Currents in Superconductors Using Freely Available Solvers for Ordinary Differential," IEEE transactions on applied superconductivity, vol. 29, no. 8, december 2019.

[5] Yazid Statra, Hocine Menana, Lamia Belguerras and Bruno Douine, "A volume integral approach for the modelling and design of HTS coils", COMPEL, vol. 38, no. 4, pp. 1133-1140, July 2019.