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

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**Abstract**—To advance the understanding of the behavior of High Temperature Superconductors (HTS) in electrical systems involving several components, it becomes relevant to couple high-end Finite Element Models (FEM) and electrical circuits made of lumped parameters. However, such an approach is often limited by the computation cost associated with computing discrete variables especially when relatively large time scales are involved such as those encountered in power systems. Nevertheless, it is a powerful tool if the system as much as the component should be detailed to understand the impact of the material on the overall response of the system. Here, a step-by-step approach is taken to validate a coupling between FEM and electrical circuits involving HTS and its response under harmonics. First, a single tape is characterized in terms of its losses, and measurements are compared to simulation results with and without circuit coupling. The same protocol is used to cross-check the FEM-Circuit coupling on a coil that targets a more complex co-simulated system.

**Keywords**—AC losses, coupled T-A formulation, co-simulation, harmonics, HTS tapes.

## I. INTRODUCTION

The next step in the development of HTS models, apart from more efficient 3D models [1]–[3], is the capability to connect HTS components to external complex electrical systems. Systems such as those found in power grids involve large scales in terms of dimensions and time constants [4]. As a first step, the inclusion of HTS technologies in the distribution grid is appealing as often they are overloaded and congested [5]. For such networks for which the system remains relatively small, the coupling FEM-Circuit may be a plausible modeling option [6]. It would allow studying the performance of HTS technology interacting with complex surroundings. In the following work, initial steps in that direction are taken with a clear focus on validating step by step the coupling FEM-Circuit to lay out the basis for the co-simulation of REBCO devices for stringent conditions with current signals that may include harmonics. Hence, the results of simulations with and without coupling are compared to experimental data obtained for a single tape and a coil. First, the measurements are carried out in a pure AC regime [7], then in AC conditions with harmonic contents by adding a diode in series with the sample. This approach provides a thorough analysis of the impact of the choice of co-simulation parameters on the accuracy of the simulation.

## II. EXPERIMENTAL SETUP AND CIRCUIT MODEL

The layout of the experimental setup is shown in Fig. 1. Two experiments are considered. The first one is without a diode to generate a pure AC signal as a reference on the AC

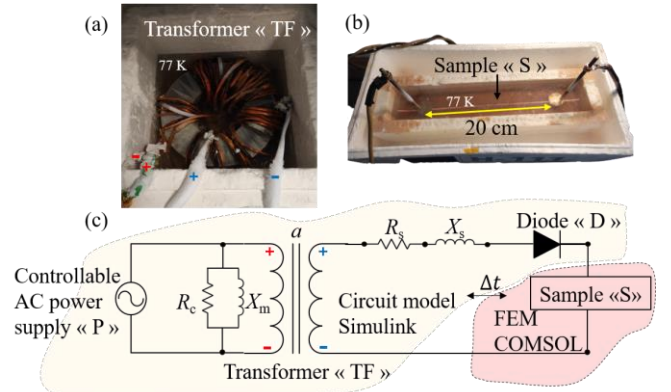


Fig. 1. (a) pictures of the transformer, (b) bath of liquid nitrogen at 77 K and single tape, (c) Schematic drawing of the experimental setup and co-simulation layout. The diode is present or absent according to the experimental protocol.

losses. The second uses a diode in series with the sample to produce harmonics as the AC current signal is clipped out over half a power cycle. Indeed, harmonics are found in power systems and are expected to affect the HTS.

As shown in Fig. 1 (a) and (b), the experimental setup consists of a home-made step-down transformer (TF) with a transformation ratio  $a = 0.13$  (secondary "s" over primary "p") feeding current to the sample (S). The sample is a single tape or a coil. The transformer, bathed in liquid nitrogen, operates at a constant temperature of 77 K to ensure consistency in the settings of the experimental setup over the time of data recording. Fig. 1 (c) shows the different parameters of the setup. It is the exact circuitry modeled in Simulink with the sample simulated by the FEM. The energy is extracted from an AC power supply (P) with controllable frequency and current amplitudes. The TF parameters modeled in Simulink were estimated via short circuit and open circuit tests.

## III. T-A FORMULATION IN FEM

The latest T-A formulation of the Maxwell equations is implemented in COMSOL Multiphysics version 5.6 for its fast computation time with a good accuracy to model REBCO technology [8]. The current vector potential  $\mathbf{T}$  is given by:

$$\frac{\partial}{\partial x} \left( \frac{\partial T_y}{\partial y} \right) = -\frac{\partial B_y}{\partial t} \quad (1)$$

and the magnetic vector potential  $\mathbf{A}$  is obtained by solving:  $\Delta \mathbf{A} = 0$ , hence providing the magnetic flux density as  $\mathbf{B} = \nabla \times \mathbf{A}$  to solve  $\mathbf{T}$ . The current is imposed as a boundary

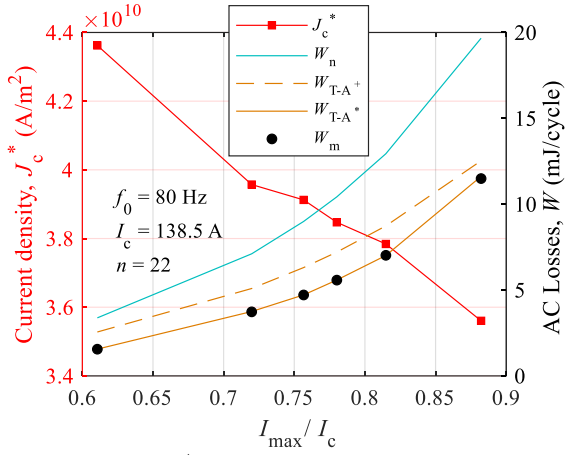


Fig. 2. Current density  $J_c^*$  (left axis, red) and AC losses per cycle  $W$  (right axis, black).  $W_n$  corresponds to the Norris' analytical model,  $W_{T-A^+}$  corresponds to the FEM results with  $J_c^+$  constant,  $W_{T-A^*}$  corresponds to a non-constant  $J_c^*$ , and  $W_m$  are the experimental data.

Dirichlet condition,  $T_1 - T_2 = I / \delta$ , with  $\delta$  the thickness of the HTS layer. The indexes 1 and 2 refer to the edges of the 1D layer. For the magnetic vector potential, the following expression is used to impose the current as a surface current,  $\mathbf{n} \cdot (\nabla \times \mathbf{H}_1 + \nabla \times \mathbf{H}_2) = \mu_0 \mathbf{K}$ , with  $\mathbf{H}_1$  and  $\mathbf{H}_2$  are the magnetic field on both side of the HTS layer and  $\mathbf{n}$  a normalized normal vector to the flat surface of the HTS layer, and  $\delta \mathbf{K} = \nabla \times \mathbf{T}$ .

#### IV. SIMULINK AND COMSOL COUPLING

The coupling between COMSOL and Simulink is provided by the LiveLink™ Module. The Matlab/Simulink model manages the global variables and decides the communication time steps from  $t$  to  $t + \Delta t$  between COMSOL and Simulink. In our study, a constant communication time step  $\Delta t$  was set in order to study the coupling even though it can be automatically decided by Simulink. For each time step, Simulink sends the instantaneous value of current to COMSOL, where the later determines the initial conditions of FEM model at  $t = t_0$ . At the end of the communication step at  $t = t_0 + \Delta t$ , COMSOL provides the resistance of the superconducting sample to be used in the Simulink model. Finally, the losses  $Q$  are computed in COMSOL and postprocessed in Matlab.

#### V. PRELIMINARY RESULTS

The AC frequencies  $f_0$  are 20, 40, 60, and 80 Hz at a fraction of the critical current  $I_{\max}/I_c$  between 60% and 90%. The bare REBCO tape, 4 mm x 0.1 mm thick, was supplied by Shanghai. The tape has a critical current of 138.5 A and a power law index  $n$  of 22. At this stage, only the tape (20 cm long) was measured in pure AC conditions at 80 Hz. Fig. 2 shows a comparison between the experimental data, the Norris' analytical formula for strips, and the FEM results without co-simulation for the initial experimental setup without the diode, see Fig. 1(c). The Norris' formula overestimates the AC losses with an average relative error of about 75%. For the FEM, two **T-A** models are considered, **T-A<sup>+</sup>** and **T-A<sup>\*</sup>**, with the same mesh size ( $d_{\text{mesh}} = 40 \mu\text{m}$ ). The **T-A<sup>+</sup>** is calculated with a constant  $J_c^+ = I_c / A_{\text{sc}}$  with  $A_{\text{sc}}$  the cross-section of the HTS layer. For the **T-A<sup>\*</sup>**, a new  $J_c^*$  is computed for each experimental loss to get the best agreement with the measurements within a 1% tolerance. The **T-A<sup>\*</sup>** model is then used to study the impact of the co-simulation parameters on the simulation results. Fig. 3 shows

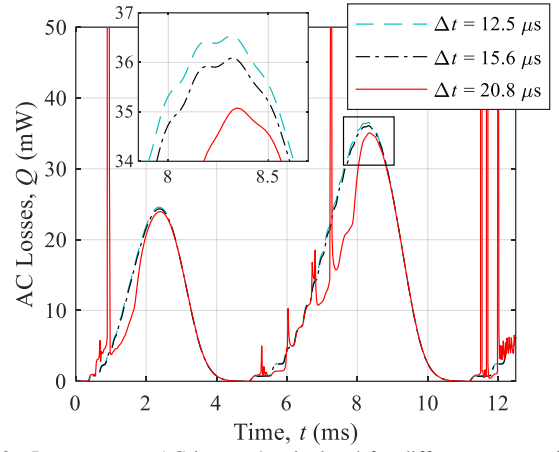


Fig. 3. Instantaneous AC losses  $Q$  calculated for different communication time steps  $\Delta t$  between COMSOL and Simulink ( $I_{\max} = 122.2$  A).

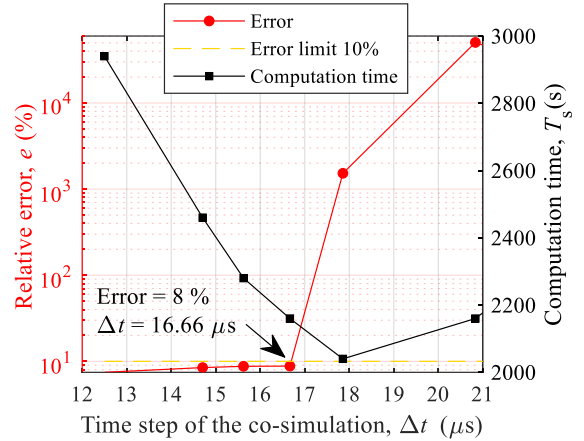


Fig. 4. Relative error  $e$  (left axis, red) and computation time (right axis, black) for  $I_{\max} = 122.2$  A and a frequency of 80 Hz as a function of the communication time step  $\Delta t$  between softwares.

the calculation of the instantaneous AC losses  $Q$  computed for  $I_{\max} = 122.2$  A at 80 Hz as a function of the communication time step  $\Delta t$ . The solver ODE 15s of Simulink is used with a relative error of  $10^{-6}$  and a maximum time step equal to  $10^{-3} / f_0 = 12.5 \mu\text{s}$ . The error on the calculation of  $Q$  increases with the increase of  $\Delta t$ . A compromise between calculation time and accuracy is found as shown in Fig. 4. For an error limit of 10% (5% measurement error + 5% model accuracy) the optimum time step is about  $16.66 \mu\text{s}$  in the present case.

#### VI. CONCLUSION

The first part of the work has been carried out on a single tape. Its AC losses have been compared to simulations. The next step is the study including the diode. Once the study on the single tape has been completed, a similar work will be carried out on a coil wound with insulated REBCO tape from the same batch as the single tape. The first results show the importance of the communication time step between the two softwares. More parameters should be still studied to complete the proposed objective. This work will provide a sound basis to build more complex co-simulation on more complex systems.

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