This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TASC.2019.2902038, IEEE Transactions on Applied Superconductivity

Over-Critical Current Resistivity of YBCO Coated Conductors through Combination of Pulsed Current Measurements and Finite Element Analysis

N. Riva, S. Richard, F. Sirois, C. Lacroix, B. Dutoit, F. Grilli

***Abstract*—Understanding the electro-thermal behavior of high temperature superconductor (HTS) materials is a critical aspect for designing efficient and reliable applications. In order to optimize cost and performance, one needs to understand the role played by the various layers of a HTS tape during a quench. On the one hand, the electrical and thermal properties of the materials used in the manufacturing of those tapes (e.g. alloy substrate, silver and copper) are well known. Knowledge of the functional dependence of the superconductor's resistivity $\rho(J,T)$ above the critical current in 2G HTS CCs is very limited. In the flux creep or normal state regime, the resistivity can be approximated by empirical laws. In the flux-flow regime, it is difficult to extract $\rho(J,T)$ due to the presence of Joule heating. In this contribution, using Finite Element Analysis (FEA), we present a method to retrieve the over-critical current resistivity, by estimating the amount of current, temperature and heat present in the various layers.**

***Index Terms*—HTS, YBCO, flux flow, over critical current, pulsed current measurements, resistivity, isothermal curves, finite element analysis**

I. INTRODUCTION

UNDERSTANDING the electro-thermal behavior of HTS materials is of paramount importance for the design and simulation of superconducting applications. Good knowledge of the over-critical current regime ($I > I_c$) is essential for applications operating near or above I_c. For instance, certain power applications or pulsed field magnetization techniques used to magnetize bulks and stack tapes require such knowledge [1]. The major challenge in retrieving such properties lies in the fact that when $I > I_c$, heating effects and thermal instabilities can quickly destroy the conductor if nothing is done to protect it. Moreover, due to the current sharing occurring between the layers, it is difficult to know the amount of current carried by the superconducting layer and, therefore, its resistivity.

To overcome these problems and characterize the over-critical current regime, we used a pulsed current measurement (PCM) technique, which can generate square current pulses in the microseconds range above I_c [2] [3]. In this contribution, the combination of the PCM technique and a post processing method through Finite Element Analysis (FEA) allowed us to correct the heating effects and to extract and validate the over-critical current resistivity of YBCO we obtained experimentally. The models presented have been implemented in COMSOL.

II. EXPERIMENTAL SETUP

A. Pulsed Current Measurements (PCM) System

The PCM system, developed at Polytechnique Montréal in collaboration with École Polytechnique Fédérale de Lausanne, allows applying very short and constant (on the plateau) current pulses with a duration as short as 15 µs, and currents between 60 A and 1600 A. With such pulses, a very small amount of energy is injected in the HTS tape, which allows reaching very high values of electric fields without destroying the tape. The reader can refer to [2] [3] for a detailed description of the PCM system.

B. Choice and Mounting of the Sample

Samples from Super Power Inc. (SF4050 line - Ag stabilizer) have been measured in liquid nitrogen (77 K). In this contribution, due to space constraints, we present the results for one sample only, which we refer to as SP01 and whose critical current at 77 K and self-field is ~ 90 A. The cross-section of SP01 is schematically represented in Fig. 1.

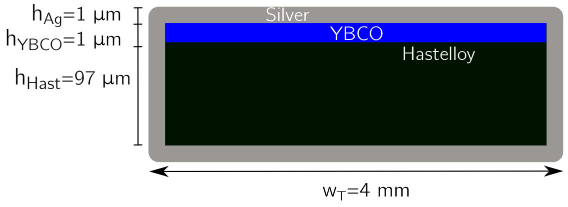


Fig. 1: Cross-section representation of the measured sample.

At the timescale (µs) and current amplitudes (hundreds of A) of the pulses used, the inductive signals affect the measurements. A sample holder developed at Polytechnique Montréal (Fig. 2) has been designed to minimize the effects of the inductive signals. The mounting of the sample allows measuring 14 voltage sections every 5 mm, plus one section that encompasses the whole length of the sample (7 cm).

This project has received funding from the Swiss Federal Office of Energy SFOE under grant agreement SI/500193-02.

N. Riva and B. Dutoit are with Ecole Polytechnique Fédérale de Lausanne, Switzerland (e-mail:nicolo.riva@epfl.ch, bertrand.dutoit@epfl.ch)

S. Richard, F. Sirois and C. Lacroix are with Polytechnique Montréal, Canada (simon.richard@polymtl.ca, f.sirois@polymtl.ca, c.lacroix@polymtl.ca)

F. Grilli is with Karlsruhe Institute of Technology (francesco.grilli@kit.edu)

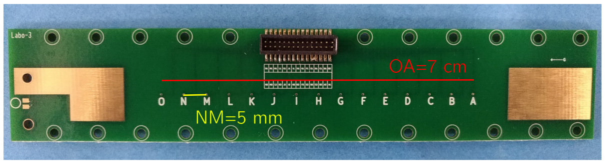


Fig. 2: Sample holder. The voltage has been measured between the contacts (A to O) every 5 mm. The distance A-O is 7 cm.

III. MEASUREMENTS

Fig. 3 presents an example of a current pulse and the corresponding voltage signal measured on the SP01 sample. At about 60 µs, there is an abrupt change in the slope of the voltage curve. To understand what happens, we first estimate the voltage drop per unit length when all the current flows in the silver and Hastelloy layers. This becomes the case when the YBCO has reached its critical temperature. We assume the critical temperature to be 92 K and to be uniform on the tape, a current $I_T = 406\,\mathrm{A}$, the following cross-sections $S_{Ag} = 0.008\,\mathrm{mm}^2$ and $S_{Hast} = 0.188\,\mathrm{mm}^2$, the resistivities $\rho_{Ag}(T = 92\,\mathrm{K}) = 3.5 \cdot 10^{-9}\Omega\,\mathrm{m}$ and $\rho_{Hast}(T = 92\,\mathrm{K}) = 1.23 \cdot 10^{-6}\Omega\,\mathrm{m}$. With the silver and Hastelloy to behave as resistors in parallel, the expected voltage drop per unit length is:

$$\frac{V}{l} = I_T \cdot \frac{\rho_{Hast} \cdot \rho_{Ag}}{\rho_{Ag} \cdot S_{Hast} + \rho_{Hast} \cdot S_{Ag}} \simeq 173\,\frac{\mathrm{V}}{\mathrm{m}}, \tag{1}$$

where l is the distance between the voltage taps. The value is shown in Fig. 3 as a black dashed line. Our simple calculation suggests that the change of slope corresponds to the time where the YBCO has reached its critical temperature.

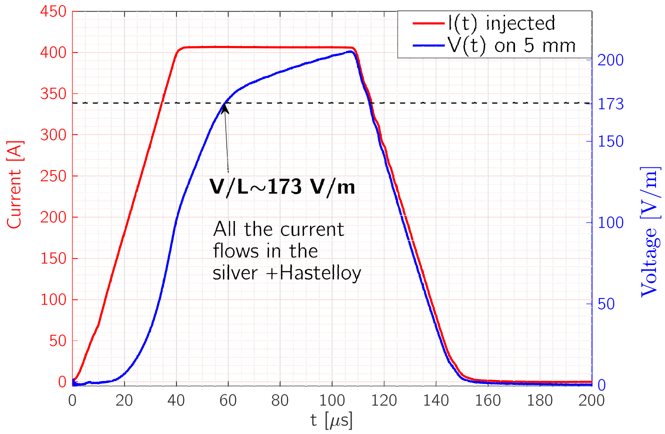


Fig. 3: Current pulse and voltage measurement on SP01.

IV. DATA ANALYSIS: EXPERIMENT AND FEA MODELLING

In this section, we describe the data analysis carried out on the measurements presented in the previous section. Using FEA modelling, it is possible to estimate the temperature over time for each layer of the HTS tape, as well as the amount of current flowing in each layer. This allows us to estimate the resistivity $\rho(J,T)$ of YBCO. A short discussion on the limits and the assumptions of the model is also presented.

A. Uniform Current (UC) 2D Model

In order to retrieve the $\rho(J,T)$ of YBCO, one should know the exact current and temperature in the superconductor, at any given time of the pulse. In the over-critical current regime, this becomes complicated, due to the current sharing between the layers. Moreover, despite the extremely short timescale of the pulses, heating cannot be neglected [4] [5].

1) Formulation of the 2D Approach: To address these problems, a FEA approach to analyze the data has been developed. In this contribution, we present a 2D model based on the geometry represented in Fig. 1. More precisely, this 2D thermal model uses the experimental data to simulate the thermal behaviour and the current sharing among the layers. The model solves the heat equation:

$$\rho_m(T)c_p(T)\frac{\partial T}{\partial t} - \nabla \cdot (k(T)\nabla T) = Q(t), \tag{2}$$

where $\rho_m(T)$ is the mass density, $c_p(T)$ is the heat capacity and $k(T)$ is the thermal conductivity.[1] The heat source is $Q(t) = J(t)E(t)$, where $J(t)$ and $E(t)$ are derived from the experimental data:

$$|E(t)| = \frac{V_{meas}(t)}{l}, \quad |J(t)| = \frac{|E(t)|}{\rho_{mat}(T)}, \tag{3}$$

where $\rho_{mat}(T)$ is the electrical resistivity of the material layer, which is known for every material except YBCO. The total current in each material $I_i^{mat}(t)$ is obtained by integrating the current density over the cross-section of each layer. Using the total measured current $I_{tot}(t)$, the current in the YBCO is obtained as:

$$I_{\mathrm{YBCO}}(t) = I_{tot}(t) - \sum_{i=1}^{n_{mat}} I_i^{mat}(t). \tag{4}$$

Finally, one obtains the resistivity of YBCO knowing the cross section of the YBCO (S_{YBCO}):

$$\rho_{\mathrm{YBCO}}(I,T) = \frac{V_{meas}(t)}{I_{\mathrm{YBCO}}(T(t))} \cdot \frac{S_{\mathrm{YBCO}}}{l}. \tag{5}$$

Due to the time scale involved, we assumed adiabatic conditions, as in previous works [3]. Future experiments will help us understand if the convective heat transfer in liquid nitrogen also plays a role here. The current density (and electric field) are assumed to be uniform on the cross-section of the YBCO layer, hence the name "uniform current model". This model does not allow calculating magnetic relaxation and other inductive phenomena that may drive spatial inhomogeneities in current density and electric field. It has been shown in [7] that this approximation is sufficient to retrieve accurately the resistivity.

2) Current Sharing and Temperature Calculated with the UC Model: An example of current sharing calculated with the UC model is presented in Fig. 4 for sample SP01, where we see the measured current $I_{tot}(t)$ and the current distribution in each layer calculated with the UC model. The temperature of YBCO, which is calculated as an average over

---

[1] All the thermal properties of the materials (silver, YBCO and Hastelloy) are known [1] [6]

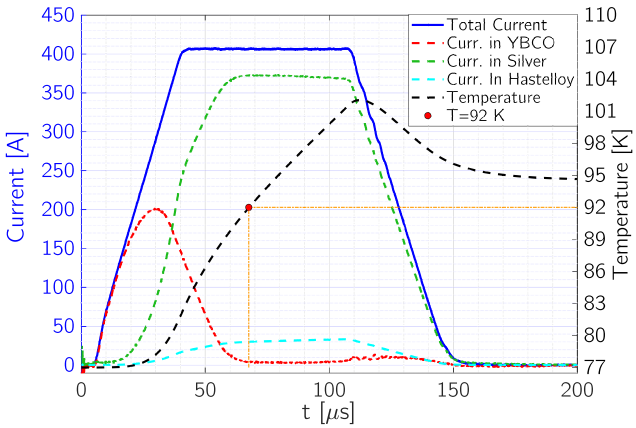


Fig. 4: Example of current sharing among layers and temperature rise in YBCO for sample SP01.

the YBCO cross-section is also shown. From the simulation results, we observe that the current in the YBCO layer drops approximately to 0 A at about 60 µs, when the corresponding temperature is 92 K. The critical temperature in self-field for these tapes is close to 92 K [8] [9]. Therefore, the UC model seems to estimate correctly the moment when the current in the YBCO layer drops to a minimum.

3) Impact of Inhomogeneities on the UC Model: Due to the possible inhomogeneous properties of the materials, the temperature and the resitivity might be not the same along the length of the sample. Since the UC model is 2D, all the physical quantities are assumed to be uniform along the length. To verify our assumption, we performed measurements at different voltage taps along sample SP01. In Fig. 5, we present three voltage measurements on three different sections of the sample, obtained during the same current pulse, and the corresponding temperatures calculated with the UC model. Despite the fact that the voltage differences measured along the length of the tape present some differences, it does not result into a remarkable deviation in the calculated temperature (less then 1 K) over the sample length characterized (the distance between sections A-B and F-G it is about 4 cm). However, it confirms that the electrical properties of the materials are not uniform along the length.

Lastly, we note that the uncertainties in the geometric parameters, such as the thickness of the silver, or the material properties, such as the resistivity of the silver, can also affect the results.

4) Resistivity Calculated with the UC Model: Using Eq. (5), the electrical resistivity of YBCO can be obtained. We estimated that the maximum error generated by the UC model is approximately 10% [7]. The red dots presented in Fig. 6 were obtained from sample SP01 using several pulses with different amplitudes, while the surface interpolating them is described in the next section.

B. Magneto-Thermal Model: Validation of Resitivity Curves

To obtain a set of resistivity data that is easy to implement in a model, we first decided to interpolate the resistivity

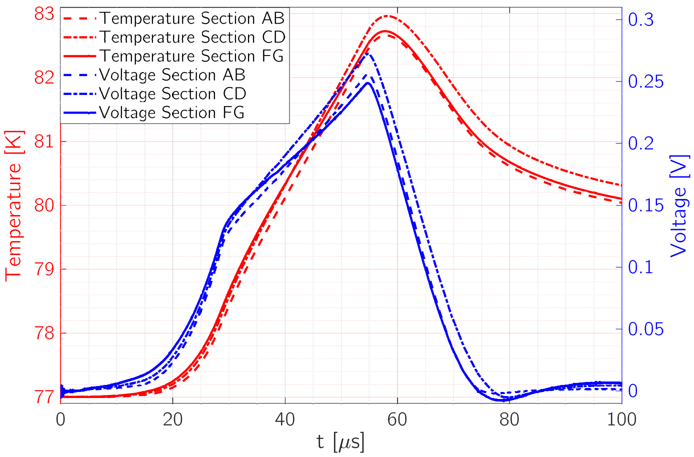


Fig. 5: Voltage measurements and temperature calculations from the UC model for sample SP01.

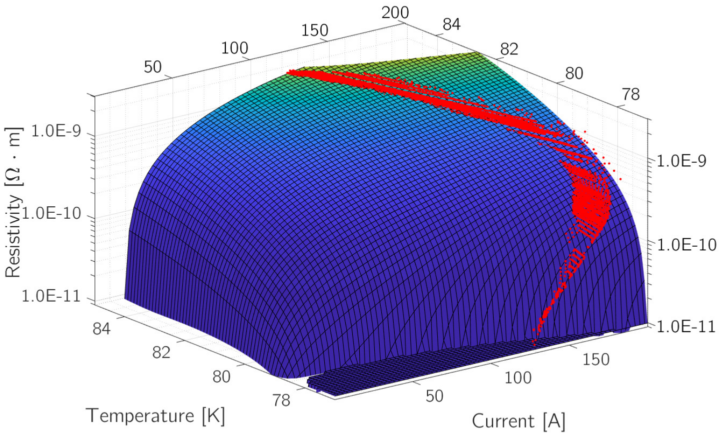
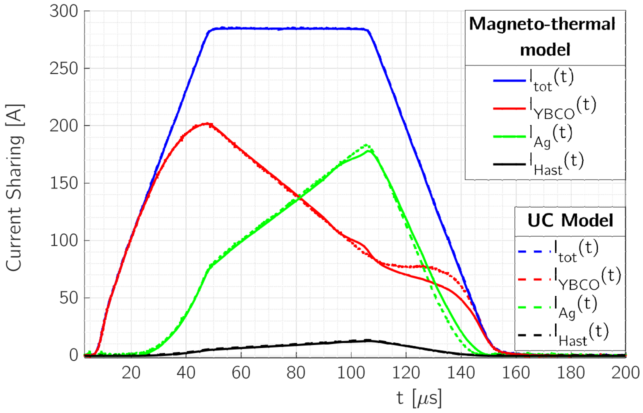
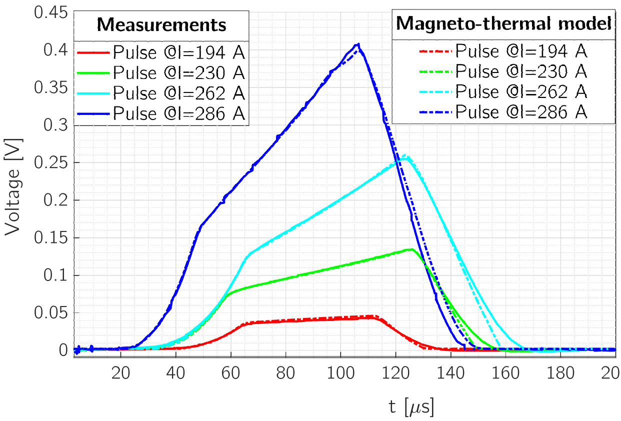


Fig. 6: Resistivity obtained from UC model (red dots) and resistivity surface $\rho(I_{\mathrm{YBCO}}, T)$ of SP01 sample.

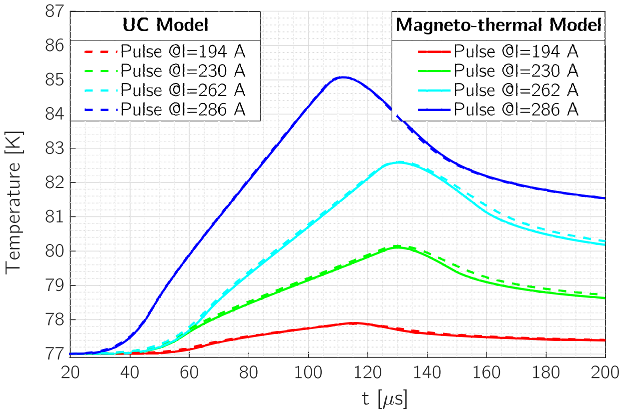
data obtained with the UC model. However, because of the replicated and collinear data [10], instead of a simple interpolation, we processed the data in order to build a smooth surface [11]. The current in Fig. 6 corresponds to the current flowing in the YBCO layer, as calculated by the UC model. Also, since the initial temperature is 77 K, the experimental data do not span the whole (ρ,I_{YBCO},T) space. Furthermore, at higher temperatures and currents, the resistivity of YBCO becomes higher than that of silver, and thus most of the current flows in the silver and Hastelloy layers. As a consequence, information on $\rho(I_{\mathrm{YBCO}}, T)$ at high temperature and high current becomes less reliable and the error generated should be further investigated. For these reasons the surface has been limited from 77 K to 85 K and 0 A to 200 A. The surface in Fig. 6 has been exported as a grid and implemented in COMSOL, with the aim of verifying the validity of $\rho(I_{\mathrm{YBCO}}, T)$ using a full magneto-thermal model [12]. This model has the same exact geometry of the UC model, except for the surrounding air computational domain, within which we solve the magnetic field. This verification ensures that assumptions such as that magnetic relaxation can be neglected are valid. The experimental voltage curves, the temperature and the current sharing calculated with the UC model, were compared with the corresponding quantities calculated with magneto-thermal model. The comparisons are shown in Fig. 7, for a current pulse of $I = 286\,\mathrm{A}$. The agreement between the two models and the measured data is very good, with an error below 1%, except in the transient region of the pulse, where the error is 15% in the worst case. The differences during the transients are due to magnetic induction in the voltage measurement realized with the sample holder, which was not modeled exactly with its real geometry. In particular the current return path has not been simulated. A rigorous estimation of the error will be discussed in future work. Eventually, we restricted the simulations performed to pulses not exceeding $85\,\mathrm{K}$, since the validity of the resistivity surface itself is limited at this temperature, for the reasons mentioned above.



(a)



(b)



(c)

Fig. 7: Comparison of the UC model with a magneto-thermal model for the SP01 sample. (a) Current sharing for a pulse of 286 A; (b) Voltage; (c) Temperature.

V. CONCLUSION

In this contribution, we have shown that with the combination of a unique experimental technique and FEA, it is possible to retrieve the resistivity characteristic of the superconducting layer in the over-critical current regime. More precisely, we developed a post-processing method through COMSOL that allows correcting heating effects from the measurements with the so-called UC model, which is a thermal model plus current sharing model. The temperature estimated by the UC model and the calculated current sharing between the layers indicate that the current in the YBCO drops to $0\,\mathrm{A}$ when its temperature reaches $92\,\mathrm{K}$, which shows that the model estimates correctly the temperature of YBCO over time. Moreover, using a magneto-thermal model, we have shown that the surface obtained from the calculated $\rho(I_{\mathrm{YBCO}}, T)$ is a very good estimation of the real resistivity and it allowed us to model the thermal and electrical behaviour of a YBCO commercial tape.

Future experimental work will include measuring the resistivity of YBCO for larger currents (up to $1600\,\mathrm{A}$) and wider temperature range ($65\,\mathrm{K}$ to $77\,\mathrm{K}$). From the modelling point of view, a sensitivity analysis has to be considered, in order to evaluate the impact of uncertainties of geometrical parameters or material properties (other than those of YBCO) on the resistivity curves. In addition, in order to improve the computational time of the models, alternative approaches to the 2D UC model will be considered, such as a simpler 1D model and/or the application of technique for reducing the computational complexity of mathematical models in numerical simulations such as Model Order Reduction (MOR) [13]. The goal is to obtain reliable data to apply in a benchmark model, so to predict in an accurate way the electro-thermal behaviour of HTS tapes and evaluate what are the benefits of the resistivity obtained from the UC model with respect to simpler models, like the power-law model.

REFERENCES

[1] S. Zou, V. M. R. Zermeño, A. Baskys, A. Patel, F. Grilli, and B. A. Glowacki, "Simulation and experiments of stacks of high temperature superconducting coated conductors magnetized by pulsed field magnetization with multi-pulse technique," *Superconductor Science and Technology*, vol. 30, no. 1, p. 014010, 2017.

[2] F. Sirois, J. Coulombe, F. Roy, and B. Dutoit, "Characterization of the electrical resistance of high temperature superconductor coated conductors at high currents using ultra-fast regulated current pulses," *Superconductor Science and Technology*, vol. 23, no. 3, pp. 3–8, 2010.

[3] F. Sirois, J. Coulombe, and A. Bernier, "Characterization of the superconducting to normal transition of HTS coated conductors by fast pulsed current measurements," *IEEE Transactions on Applied Superconductivity*, vol. 19, no. 3, pp. 3585–3590, 2009.

[4] M. Therasse, M. Decroux, L. Antognazza, M. Abplanalp, and O. Fischer, "Electrical characteristics of DyBCO coated conductors at high current densities for fault current limiter application," *Physica C: Superconductivity*, vol. 468, no. 21, pp. 2191–2196, 2008.

[5] F. Sirois, C. Lacroix, B. Dutoit, J.-p. Corbeil, and J. Coulombe, "Flux flow characteristics of 2G HTS coated conductors measured with microsecond- range pulsed currents," pp. 1–28, 2015.

[6] HTS MODELING WORKGROUP, "HTS Modelling Website," 2012. [Online]. Available: http://www.htsmodelling.com/?page_id=1039

[7] S. Richard, F. Sirois, and C. Lacroix, "Development of a characterization method of the resistance of 2G HTS CCs tapes above Ic in static condition with ultra-fast current pulses," *To be published*.

[8] M. K. Wu, J. R. Ashburn, C. J. Torng, P. H. Hor, R. L. Meng, L. Gao, Z. J. Huang, Y. Q. Wang, and C. W. Chu, "Superconductivity at 93 K in a new mixed-phase Y-Ba-Cu-O compound system at ambient pressure," *Physical Review Letters*, vol. 58, no. 9, pp. 908–910, 3 1987.

[9] D. W. Hazelton, "2G HTS Wire Development at SuperPower," pp. Accessed on Sept. 1, 2017., 2016. [Online]. Available: https://nationalmaglab.org/images/magnet_development/asc/searchable_docs/asc_resources/coated_conductors/2016/io_14_hazelton.pdf

[10] D. T. Sandwell, "Biharmonic spline interpolation of GEOS3 and SEASAT altimeter data," *Geophysical Research Letter*, pp. 139–142, 1987.

[11] J. D'Errico, "Understanding Gridfit. Surface Fitting using Gridfit," in *Online*. [Online]. Available: http://www.mathworks.com/matlabcentral/fileexchange/loadFile

[12] R. Brambilla, F. Grilli, and L. Martini, "Development of an edge-element model for AC loss computation of high-temperature superconductors," *Superconductor Science and Technology*, vol. 20, no. 1, pp. 16–24, 2007.

[13] A. Quarteroni and G. Rozza, *Reduced Order Methods for Modeling and Computational Reduction*. Springer Publishing Company, Incorporated, 2013.