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EDITORIAL

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Editorial

The 5th international workshop on numerical modelling of high temperature superconductors

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High Temperature Superconductors (HTS) are advanced materials, which allow the development of devices with unachieved performance, as well as new functionalities. Further advantages are a drastic increase in efficiency from the materials' zero (DC) to near zero (AC) resistivity, increased device compactness from the significantly larger current-carrying capability and the possibility of longer device lifespans. Numerical modelling is an essential tool for the design and optimisation of practical HTS devices and for improving understanding of the fundamental properties of HTS materials.

The modelling of HTS materials must incorporate very complex behaviour due to extreme nonlinearity and hysteresis, strong anisotropy, temperature dependence, relaxation and the high aspect ratio and complex composite structure of practical wires and tapes. Such complex behaviour raises new challenges in the development of reliable modelling tools and requires a specialised research effort to effectively deal with these problems. Hence, a series of international workshops dedicated to the numerical modelling of HTS has been organized since 2010 with the support of the HTS modelling workgroup [1]. The aim is to stimulate discussion and collaboration among experts in order to produce advances in modelling methods and tools needed for the development of HTS science and technology. Previous highly successful editions were held in Lausanne, Cambridge, Barcelona and Bratislava.

The 5th International Workshop on Numerical Modelling of HTS was held in Bologna, Italy, on 15–17 June 2016. The workshop received 71 abstracts submitted for presentation and was attended by 92 registered participants. Submitted abstracts were rated by the workshop's International Scientific Committee and organized over 37 oral presentations and 34 poster presentations. The top-rated contributions were invited to submit a full-length research manuscript for possible publication in Superconductor Science and Technology after the standard peer review process. The selected papers accepted for publication are collected in this special Focus on Numerical Modelling of HTS. The main topics covered by the focus issue are described as follows, where only papers appearing in the special issue are cited:

Modelling of phenomena relevant for HTS applications

In Ainslie *et al* [2], a 2D axisymmetric numerical modelling framework based on the H-formulation is implemented for investigating the 'giant field leap' effect observed during pulsed field magnetisation of cylindrical bulk HTS samples with large J_c values. The model is able to reproduce the observed results of magnetic flux suddenly intruding into the centre of the sample, without the need for any new physics to explain the physical mechanism. A bounded E–J power law, able to naturally link the flux creep and the flux flow regime, is used to increase the accuracy of the numerical solution and to improve the convergence properties of the model.

In Bykovsky *et al* [3], the magnetisation loss for stacks of ReBCO tapes are investigated numerically and compared with experiments. The influence on the magnetisation loss of the number of tapes, width of the tape, magnetic field orientation and tape manufacturer is studied. Based on the numerical results, an analytical approach for estimating the magnetisation loss in stacks of tapes with an arbitrary number of tapes under the assumption of the critical state model is developed.

In Ruuskanen *et al* [4], a 2D model for evaluating the hysteresis loss of Roebel-cable-based accelerator magnets during ramp-up is developed. The model exploits the critical state model of the material, combined with the minimum magnetic energy variation principle for calculating the numerical solution. An open-source software package, suitable for large-scale nonlinear optimisation problems, is used for minimising the functional. The use of the critical state allows one to avoid the overestimation of losses which is obtained by using the power law, due to the fact that a non-zero electric field is associated with any non-zero current.

In Campbell *et al* [5], the crossed field decay of the trapped magnetisation of thin strip superconductors, and stacks thereof, are investigated numerically using two finite element method-based modelling frameworks: FlexPDE with the A-formulation and COMSOL with the H-formulation. The simulations show good agreement with the relevant theory developed by Brandt and Mikitik and confirm that the decay in very thin sheets is slow, even when the applied transverse field is much greater than the transverse penetration field.

In Zermeno *et al* [6], a method is developed for extracting the dependence of the critical current density J_c of a superconductor on the local magnetic field $\boldsymbol{B}_{loc}$, starting from the experimental data relating the critical current, I_c, of a tape to the external applied field $\boldsymbol{B}_a$. The output of the method is a set of J_c-$\boldsymbol{B}_{loc}$ data that, once interpolated, can be used as the material's properties for successive simulations of low-field-operating HTS devices, such as resistive fault current limiter or power cables, for which the effect of the self-field could cause inaccuracy in results.

In Gömöry *et al* [7], a method is developed for calculating the total AC loss of a coil, based both on local quantities (scalar product of E and J) and on global quantities (overall current and voltage of the coil), the latter of which are observable during experiments. It is suggested that possible differences between the two approaches can be used for identifying numerical errors from the calculations. The approach is implemented both for the A-ϕ and the H-formulations. A model for calculating the voltage of the coil as a post-processing variable when using the H-formulation is developed.

3D and quasi-3D modelling

In Escamez *et al* [8], a 3D numerical model for the calculation of AC losses in an MgB_2 multi-filamentary wire subject to AC transport current and applied field is developed. The wire is made of 36 twisted filaments embedded within a resistive and ferromagnetic matrix. The model exploits the finite-element approach based on the H-formulation and is able to take into account the coupling and eddy current losses, without considering, so far, the effect of the resistive barriers surrounding the SC filaments. Data on the electrical and magnetic properties of all constitutive materials of the wire, obtained by extensive characterisation, are also reported.

In Pardo *et al* [9], a method is developed for calculating the current and field distribution in homogeneous 3D bulks subject to an applied field and/or transport current. The method is based on the Minimum Electro-Magnetic Entropy Production approach in 3D (MEMEP3D), which allows dealing with the high number of degrees of freedom needed for the analysis of actual 3D problems. The method is used for investigating the current density, saturation field and magnetisation loops of rectangular prisms with a square base and for several height-to-width aspect ratios. Non-rectangular current paths are found for applied fields below the saturation value for cubic-like geometries, which have a significant influence on the magnetic field produced at the surface.

In Zhang *et al* [10], a numerical model for calculating the current distribution and AC loss of 2G HTS tapes or coils is developed. The model assumes the thin sheet approximation for the HTS tape and is based on a hybrid *T–A* formulation that allows an easy assignment of the boundary conditions. The model is validated against an analytical solution for a 1D case (magnetisation of a thin disk) and is successfully applied to complex geometries such as a twisted stacked tapes conductor subjected to an applied magnetic field and a racetrack coil with a transport current.

Innovative modelling and dissemination tools

In Peña-Roche *et al* [11], an app is developed for the numerical investigation of 2D magnetic levitation systems. More specifically, well-established physical models are implemented in the form of a utility for portable devices. A hybrid strategy is used that combines, via wireless or cable communication, pre-processing in a high performance computer and the final post-processing on the portable device. The app is well suited to provide information on hysteresis effects, so as to contribute to training and dissemination and to complement computer-based tools for Maglev design.

Modelling of the interaction of HTS devices with the power network

In Bonnard *et al* [12], a multiscale model is developed to investigate behaviour of the resistive fault current limiter. In particular, depending on the discretisation used, the model is able to take into account the relevant phenomena affecting the performance of the device, e.g., hot spots and diffusion of heat across the thickness of the tape. Remarkably, the model is implemented in the EMTP-RV environment, which is a professional power system simulator. This enables the accurate evaluation of the transient response and the effect of the device when it interacts with real-world power grids.

Modelling of Josephson junctions systems

In Shukrinov *et al* [13], resonance phenomena in a model of intrinsic Josephson Junctions shunted by LC-elements are studied. The phase dynamics and IV characteristics are investigated in detail when the Josephson frequency approaches the frequency of the resonance circuit. A realisation of parametric resonance through the excitation of a longitudinal plasma wave, within the bias current interval corresponding to the resonance circuit branch, is demonstrated. The authors found that the temporal dependence of the total voltage of the stack, and the voltage measured across the shunt capacitor, reflect the charging of superconducting layers, a phenomenon that might be useful as a means of detecting such charging experimentally. Based on the voltage dynamics, a novel method for the determination of charging in the superconducting layers of coupled Josephson junctions is proposed. A demonstration and discussion of the influence of external electromagnetic radiation on IV characteristics and charge-time dependence is given. Over certain parameter ranges the radiation causes an interesting new type of temporal splitting in the charge-time oscillations within the superconducting layers.

Future outlook and challenges

Towards the end of the workshop, participants formed groups to discuss current and future challenges for numerical modelling in a number of key areas: (1) fundamental aspects and physics, (2) tapes, cables and coils, (3) multi-physics and multiscale problems, and (4) mathematical tools and software applicable to HTS modelling.

The following highlights were presented in the summaries of the group discussions:

Fundamental aspects and physics

3D critical state modelling is still an open problem, especially concerning crossed-field effects and the constitutive law between E and J, such as the E–J power law, when E and J are not parallel to each other. Recent attempts, like the double critical-state model (CSM), do not appear to be a valid solution. A theoretical explanation for the time dependence of the trapped field in bulk superconductors acting as trapped field magnets remains open as well: experimental results have shown a plateau in the remanent magnetisation shortly after magnetisation that tends towards logarithmic or faster decay. A new benchmark (full 3D) problem—the magnetisation of an HTS cube—was established, and some solutions are already available on the HTS Modelling Workgroup's website (Benchmark #5) [14]. Finally, it would be interesting to attempt to recover the CSM limit, for the case of a certain number of flux lines, using calculations based on the Ginzburg–Landau formalism.

Tapes, cables and coils

The issue of long computing times for simulations, even for large-scale coils, does not seem to be a problem any more thanks to the possibility of using the 'effective' turns instead of real turns, modification of the aspect ratio of coated conductors, and simultaneous computations using parallel computing. A material properties database for modellers could be a very important outcome from the community in the near future. Collated data relevant to the electrical and thermal properties of HTS coated conductors is now available on the HTS Modeling Workgroup's webpage. Several tailored simulation tools have been implemented in different institutions for various purposes. The community strongly supports the exchange of these, and the relevant documentation, including related publications, to make the tools/models available to other scientists in the field.

Mathematical tools and software

Analytical approaches and solutions to situations where they are applicable are now highly mature and it is difficult to push many new developments, especially for more complex problems. New, alternative numerical modelling techniques are being developed that challenge the commonly used, finite element method-based approaches. These include the boundary element method, the fast multipole method, and mixed approaches combining different methods. Meshless methods may be useful for HTS modelling, but this has not been explored in great detail to date. Again, there is a clear trend for publishing codes open source and this can fast-track the exchange of codes. 3D modelling for general simulation situations is still coming, and only specific tools can solve specific or superficial problems. It is strongly recommended that the community improve coupling with experts in numerical analysis to accelerate developments HTS modelling.

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