HTS MODELLING 2018

6th International Workshop on Numerical Modelling of High Temperature Superconductors

FCT NOVA, Caparica, Portugal

26 – 29 June 2018

PROGRAMME

IEEE CSC Council on Superconductivity · EERA Energy Storage · HTS MODELLING WORKGROUP · FCT Faculdade de Ciências e Tecnologia Universidade Nova de Lisboa · UNINOVA - CTS

PROGRAMME

	Tuesday 26 June 2018	Wednesday 27 June 2018	Thursday 28 June 2018	Friday 29 June 2018
08:00				
09:00		**Opening Ceremony** **Plenary 1**	**Plenary 2** **Invited Talk: AC losses**	**3D Modelling**
10:00		*Coffee Break*	*Coffee Break*	*Coffee Break*
11:00		**Machines**	**AC losses** and **Miscellaneous II**	**High Field Magnets** and **Grid Applications**
12:00				
13:00		*Lunch*	*Lunch*	*Lunch*
14:00		**Quench**	**Posters**	**Maglev** and **Bearings**
15:00				
16:00		*Coffee Break*	*Coffee Break*	**Discussion, wrap-up and closing**
17:00	**EERA Roundtable**	**Bulks and Hybrid Structures** and **Miscellaneous I**	**Mechanical Aspects** and **Numerical Modelling**	
18:00				
19:00	**Welcome Reception**	**Social Event Portuguese "*Arraial*"**	**Gala Dinner**	

DETAILED PROGRAMME

TUESDAY, 26 JUNE 2018

15:00 Registration opens (Building VII)

16:30 – 18:00 EERA Roundtable

18:00 – 20:00 Welcome Reception

WEDNESDAY, 27 JUNE 2018

08:45 – 09:15 Opening Ceremony

09:15 – 10:15 Plenary 1

Chair:
Paulo Branco, Instituto Superior Técnico, Portugal

HPC for solving multi-physics problems

Dr. Xavier Sáez
Barcelona Supercomputing Center (BSC), Catalonia, Spain

The use of computational models is widespread in the engineering designs and manufacturing processes. A multi-physics approach is often required to capture all relevant phenomena to model and simulate complex systems such as safe cars and energy-efficient aircrafts. High-Performance Computing (HPC) plays an essential role in such multi-physics simulations due to the high computing resources required.
Alya is a multi-physics simulation code developed at Barcelona Supercomputing Center (BSC). From its inception, Alya has been designed to solve coupled problems with HPC efficiently and with the flexibility to add new physics models. Its target domain is engineering, with complex geometries, unstructured meshes and coupled multi-physics.
This talk will present selected multi-physics examples solved by Alya that are representative of the engineering world and require the computing power of a supercomputer, such as a flow for wind energy generation, a low Mach combustion problem, and a coupled electro-mechanical contraction of the heart.

10:15 – 10:45 Coffee Break

10:45 – 12:45 Oral 1 – Machines

Chairs:
Enric Pardo, Slovak Academy of Sciences, Slovak Republic
Xavier Granados, Institute of Materials Science of Barcelona, Catalonia, Spain

O1-09

User Defined Elements in ANSYS for 2D Multiphysics Modeling of Bi2212 Racetrack Coils

Lucas Brouwer[1], Diego Arbelaez[1], Daniel Davis[2], Tengming Shen[1] and Soren Prestemon[1]
[1]Lawrence Berkeley National Laboratory, United States of America, [2]Florida State University, United States of America

The finite element software ANSYS is widely used for mechanical, thermal, and magnetic modeling of superconducting magnets. Within ANSYS there is the capability for users to create their own element type by writing the code which defines the element's properties and the generation of its finite element matrices. After the compilation of a custom ANSYS executable, all other aspects of the software (such as geometry generation, meshing, solving, and post-processing) are compatible with the user element. Control over the generation of the matrices allows for customization of the mathematical formulation, material properties, and many other aspects of the element. We report on the development of two user defined elements: one thermal, and one electromagnetic with circuit coupling. These replicate and extend the capabilities of ANSYS for simulation of superconducting magnets to now include the effects of current sharing, quench propagation, temperature and field dependent material properties, and interfilament coupling currents. A combined solution using these two elements with the ANSYS multi-field solver is shown simulating coupled transient electromagnetic, thermal, and circuit effects for a common coil dipole magnet consisted of two Bi2212 racetrack coils built and tested at Lawrence Berkeley National Laboratory. The effects of current sharing, interfilament coupling currents, and structural eddy currents are studied and compared to data from several magnet tests.

O1-10 Ripple field effects on the no-insulation high-temperature superconductor rotor windings of machines

Yawei Wang, Zixuan Zhu, Min Zhang and Weijia Yuan
University of Bath, United Kingdom

A high self-protecting high temperature superconductor (HTS) machine technique is being developed for all electrical aircraft in Bath University, UK. No-insulation (NI) winding technique is applied on rotor windings of the synchronous machine to enhance its thermal stability and reliability. However, eddy current between turns is induced on the NI rotor windings by the ripple field from the stator windings, due to the absence of turn-to-turn insulation. Joule loss induced by the eddy current, which is called 'turn-to-turn loss' in this study, may affect considerably on the efficiency of the machine. To study the losses of NI coils induced by ripple field, a numerical mode is developed by coupling an equivalent circuit network model and an H-formulation finite element method (FEM) model. In the equivalent circuit model, each turn of the NI coil is subdivided into fine arc element, each arc element is equivalent to lumped circuit model, and the whole coil is equivalent to a circuit network. This model is to calculate the eddy current and the turn-to-turn loss between turns. The FEM model based on H-formulation is to calculate the magnetization loss in superconductors induced by ripple field. A NI coil is wound by REBCO tapes, and it is tested under ripple magnetic field with a DC field bias, which is to simulate the machine magnetic environment. The eddy loss induced by the ripple field is measured using calibration-free method. The results from simulation and experiments are compared to validate the above model. Then the turn-to-turn loss and magnetization loss of a NI HTS rotor magnet is analyzed using the model, and comparison is conducted with its insulated counterpart. A grading turn-to-turn resistivity is proposed to reduce the total losses (including the turn-to-turn loss and magnetization loss) of NI HTS rotor windings induced by ripple fields.

O1-17 A finite element method framework for modeling rotating machines with superconducting windings

Roberto Brambilla[1], Francesco Grilli[2], Luciano Martini[1], Marco Bocchi[1] and Giuliano Angeli[1]
[1]Ricerca sul Sistema Energetico, Italy, [2]Karlsruhe Institute of Technology, Germany

Electrical machines employing superconductors are attractive solutions in a variety of application domains. Numerical models are powerful and necessary tools to optimize their design and predict their performance. The electromagnetic modeling of superconductors by finite-element method (FEM) is usually based on a power-law resistivity for their electrical behavior. The implementation of such constitutive law in conventional models of electrical machines is quite problematic: the magnetic vector potential directly gives the electric field and requires using a power-law depending on it. This power-law is a non-bounded function that can generate enormous uneven values in low electric field regions that can destroy the reliability of solutions.
The method proposed here consists in separating the model of an electrical machine in two parts, where the magnetic field is calculated with the most appropriate formulation: the H-formulation in the part containing the superconductors and the A-formulation in the part containing conventional conductors (and possibly permanent magnets). The main goal of this work is to determine and to correctly apply the continuity conditions on the boundary separating the two regions. Depending on the location of such boundary – in the fixed or rotating part of the machine – the conditions that one needs to apply are different. In addition, the application of those conditions requires the use of Lagrange multipliers satisfying the field transforms of the electromagnetic quantities in the two reference systems, the fixed and the rotating one. In this article, several exemplary cases for the possible configurations are presented. In order to emphasize and capture the essential point of this modeling strategy, the discussed examples are rather simple. Nevertheless, they constitute a solid starting point for modeling more complex and realistic devices.

O1-19 Modeling and Design of HTS Machines - New Challenges for Calculation Methods

Simon Wolfstaedter and Thomas Reis
Oswald Elektromotoren GmbH, Germany

This paper describes the layout and design process of high temperature superconductive machines. The similarities as well as the new challenges to the modeling and calculation in comparison to classical normal conductive machines are shown. Typical finite element calculation methods for examining and evaluating the electromagnetic properties of an electrical machine and the possibility of using them for superconducting applications are presented. In particular, the penetrating magnetic flux density in the environment of superconductors, the concomitant reduction of the critical current and the influence on the total losses require a precise numerical analysis of the system. Due to field fluctuations in AC applications a whole mechanical period has to be considered. The observation of steady state conditions, as in DC operation, is not sufficient. For these reasons, the development of efficient and less time consuming computational methods,

for modeling superconducting electrical machines from an industrial and commercial point of view, is very important.

O1-23 Simulation of Synchronous-Hysteresis Superconducting Machine

Bárbara Maria Oliveira Santos[1], Fernando Dias[1], Felipe Sass[2], Guilherme Sotelo[2], Alexander Polasek[3] and Rubens de Andrade Junior[1]
[1]Universidade Federal do Rio de Janeiro, Brazil, [2]Universidade Federal Fluminense, Brazil, [3]Centro de Pesquisas de Energia Elétrica, Brazil

Superconducting electric machines (SEM) are usually designed to use superconducting bulks with trapped field or superconducting tapes as coils. The replacement of bulks by stacks of 2G HTS tapes to trap the magnetic field in electric machines has been proposed in some works, but it has not been thoroughly discussed in the literature. This work is part of a project that investigates a SEM topology in which the rotor is composed of stacks of 2G HTS tapes arranged around a ferromagnetic cylinder. This machine has two modes of operation, a synchronous one, with no AC losses in the rotor, and a hysteresis one, with AC losses and slip. Two 2D simulation models are presented, focusing on the synchronous mode of operation. The simulated prototype consists of a three phase six pole machine. In the first 2D simulation model, no mesh movement was considered. H formulation was used as mathematical model. The stack of tapes was represented via the homogenization method and Jc was kept constant. Two stator topologies were simulated, one with thirty six slots and other with seventy two slots. As a result, the induced current density in the ring accompanies the poles with maximum and minimum values equal to Jc and no significant difference was observed as the number of slots was increased. In the second model, mesh movement was considered. A-V formulation was used, along with the homogenization method and Jc varying with B with the Kim model. The induced current density has the same behavior as before, except for oscillations around the maximum and minimum values. Comparisons of quasi-static torque, torque at locked rotor and torque – speed characteristics between simulation results and measurements made at the laboratory are also presented.

O1-50 In situ magnetisation strategies for trapped field magnets made of stacked HTS tapes in electric machines

Algirdas Baskys, Anup Patel, Vicente Climente-Alarcon and Bartek Glowacki
University of Cambridge, United Kingdom

Trapped field magnets (TFM) made of stacks of 2G HTS coated conductors have demonstrated strong potential to be used as large, purpose shaped field poles in a rotor of an electric machine and replace conventional permanent magnets. Such trapped field magnets can generate field up to an order of magnitude higher than rare earth ferromagnetic materials, allowing for higher torque and power densities, enabling their use in mobile/transport applications. Nevertheless, before such TFMs can be used in a machine, effective magnetisation strategies must be developed. This work explores the options for magnetising a superconducting trapped field magnet, in situ, inside an electric machine. Several strategies are considered that include pulsed field and field cooling magnetisation with or without presence of iron in the stator and the rotor, which has a strong effect on the magnetic flux density magnitude, distribution and time dependent flux evolution during magnetisation procedure. Sequential magnetisation procedure of individual field poles and 'one-shot' magnetisation is discussed. In the case of sequential magnetisation, a substantial force is required to position the rotor in the exact location for magnetisation, once several poles are already magnetised. Moreover, the effect of cross-magnetising adjacent, already magnetised poles during sequential magnetisation procedure is discussed. These problems were elaborated by conducting time dependent FEM simulations using H formulation together with magnetic vector and scalar potentials describing different parts of the model. This allows rotation and use of non-continuous mesh interfaces moving relative to each other. The simulations were conducted using COMSOL Multiphysics 5.3a.

12:45 – 13:45 **Lunch**

13:45 – 15:45 Oral 2 – Quench

Chairs:
Kévin Berger, GREEN, Université de Lorraine, France
Fedor Gömöry, Slovak Academy of Sciences, Slovak Republic

O2-41 Analysis of Performance during Quench of a Pancake coil wound with REBCO Roebel cable

Lorenzo Cavallucci[1], Marco Breschi[1], Pier Luigi Ribani[1], Qingbo Zhang[2] and Yifeng Yang[2]
University of Bologna, Italy, University of Southampton, United Kingdom

Roebel cables assembled with HTS tapes are a promising technology for several AC and DC applications. The continuous transposition of strands, the ability to efficiently redistribute current, the compact design,

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combined with the capability of REBCO tapes to operate at high magnetic fields allow Roebel-based devices to carry large transport currents with reduced AC losses. These features make them suitable for application at intense magnetic fields, such as in accelerator and fusion magnets.
In this paper, a novel "quasi-3D" electro-thermal Finite Element model is discussed and applied to the analysis of performance and quench behavior of a 7-turn pancake coil wound with a 2-m long, 15-strand Roebel cable. The code simulates the current and heat flux redistribution through distributed thermal and electrical contacts between strands. The simulation results are compared with experimental data obtained in quench tests carried out at the University of Southampton (UK) in the frame of the EuCARD-2 European project. The quench decision time, the temperature and electric potential evolution and the current and heat flux redistribution between strands during the quench event are analysed and discussed in this study.

O2-55 Simulation study on quench protection system of HTS coil using Cu tape co-wound with HTS tape

Akane Kojima, Hifumi Toriyama, Yoshiki Fuchida, Akihiro Nomoto, Tomoaki Takao, Kazuya Nakamura and Osami Tsukamoto
Sophia University, Japan

In recent progresses of R&Ds of HTS applications, i.e. motors, generators and MRI, it is realized that sure quench protection of HTS coils is essential for their sustainable operations. A common and basic method to protect an HTS coil is a detect-and-dump method as follows. When the voltage across the resistive zone Rs appearing in the coil Vs exceeds a certain threshold value Vq, the quench protection sequence starts disconnecting the coil from the power supply and dumping the stored energy of the coil into the dump-resister Rd. When the highest temperature at the resistive zone of the coil wire during the quench protection sequence (Hot-spot temperature THS) exceeds a certain threshold value THSs, the coil is damaged. The value of Vq is necessary to determine to surely keep THS below THSs. To keep THS below THSs, especially in an HTS coil of high current-density winding pack, the value of Vq should be strictly below its threshold value Vqs which depends on the coil current and the decay time constant of the coil current τ (= L / Rd, L: inductance of the coil) during quench protection sequence. When Vq exceeds Vqs even slightly, THS exceeds THSs. As the value of τ increases, the Vqs becomes smaller and a highly sensitive quench detection method is required which often malfunctions due to noises. Therefore, it is important to develop a quench protection method which can increase the values of Vqs while increasing τ.
The authors conducted a simulation study on a quench protection system of HTS coil using Cu tape co-wound with HTS tape. In the normal operation, the voltage across the resistive zone Vs which may appear in the HTS coil is monitored by monitoring the voltage difference Vdiff between the HTS coil and the co-wound coil. The value of Vs is approximated by that of Vdiff with good accuracy because the both coils are magnetically coupled tightly. When Vs exceeds the quench detection voltage Vq, the HTS coil is disconnected from the power apply and the stored energy of the HTS coil starts to be dumped into the dump resistor R1. At the same time, a voltage is induced in the co-wound coil and a switch to connect the co-wound coil to a resister R2 is closed. to induce a current in the co-wound coil and R2. Then, a part of the currents of the HTS coil is quickly transferred to the co-wound Cu tape coil because of the tight magnetic coupling of the both coils, and the HTS coil current is decreased rapidly to a certain value just after the quench protection sequence starts. Therefore, it is expected that the temperature at the resistive zone, that is THS, is decreased. Amount of the current transferred from the HTS coil to the co-wound coil can be adjusted by the value of α = R2 /R1. However, it should be noted that the current I2 transferred from the HTS coil joule-heats the Cu tape, and there is a possibility that the Cu tape burns out if it does not have enough thickness. The thick Cu tape deteriorates the current density of the winding pack of the coil. Therefore, its thickness should be properly determined not to burn while keeping THS below the safe level in the relation of the value of α.
The authors investigate dependence of THS onτ, α and the thickness of the Cu tape for an YBCO model coil by a numerical simulation analysis based on a thermal model of the coil and discuss effectiveness of this quench protection method.
Acknowledgement: This work is based on results obtained from a project commission by the NEDO.

O2-61 Calculation of the local current density in a coil using a volume integral formulation to obtain an accurate evaluation of the local critical current variations

Blandine Rozier, Brahim Ramdane, Arnaud Badel, Gérard Meunier and Pascal Tixador
G2ELab, France

The use of REBCO (Rare-Earth BaCuO) High Temperature Superconductors for magnet applications is widely studied. The difficulty is that REBCO tapes are highly thermally stable but rather inhomogeneous in terms of critical current (Ic). This leads a significant risk of damaging hot spots when operating close to the estimated critical current. In order to study these local dissipation phenomena, we developed an electro-thermal quench propagation model focusing on the impact of HTS tape Ic inhomogeneities on local transition occurrence and propagation. This Ic inhomogeneity comes from two sources: the local inhomogeneities of the tapes, and the variations in the local operation conditions: temperature, magnetic field amplitude and angle. We consider in

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that model that the local Ic anywhere in a given application is given by the local Ic at 77K self-field (obtained by continuous inductive measurement), multiplied by a “local lift factor” accounting for the local operation conditions.

Defining this local lift factor variations in a given application, in our case a magnet, (solenoid or simple pancake coil) is the object of this work. We will take as an input the critical current density variation Jc (T,B,Theta) of the tape obtained through short sample characterizations made in conditions in which the full sample is submitted to a homogenous magnetic field, both in terms of amplitude and orientation. The local current density distribution in each of the magnet turns is evaluated using a transient 2D axisymmetric electro-magnetic model, in order to account for the effect of local magnetic field variation across the magnet turns.

The current at which dissipative state is reached is evaluated for each turn to obtain what we call the local lift factor, to be later injected in quench models.

For such axisymmetric electro-magnetic models, Finite Element Method has been used successfully by other teams, but the mesh associated with the thin regions representing each turns has to be carefully defined in order to ensure the nonlinear convergence. Meshing large air regions between superconducting layers can turn out to be very difficult, especially if different elements are used (such as mapped mesh inside the superconducting layer and triangle mesh for air regions). The cost of such computations rapidly explodes as the number of turns increases. The Partial Element Equivalent Circuit method appears to be an interesting approach to represent lots of thin conducting layers separated by large air regions as long as the latter has not to be meshed anymore. Moreover, the conservation of current density is strongly ensured by using the circuit approach. However, the equivalent circuit construction as well as the computation of independent voltage loops represent a consequent task and is very specific to each geometry. We propose an original and more flexible approach based on a volume integral formulation. It combines the advantages of the PEEC method by meshing only conducting parts of the whole domain and enforcing the conservation of current, and of FEM as it requires only a basic meshing tool to generate the equivalent circuit. In our case, degrees of freedom are associated with the flux of current density through the elements. The axisymmetric behavior is taken into account through a slight modification of the usual 3D Green kernel used in integral methods. The E(J) characteristic of superconductors is modelled using a power law. A Newton-Raphson algorithm gives the current distribution inside each conductor for every time step. The magnetic field produced by the current distribution is then calculated at every Gauss points of the conducting domain to adapt the local Jc to magnetic field variations. For the time discretization, a Backward Euler schema has been chosen due to its intrinsic stability. Adaptive time-stepping methods have also been implemented to reduce the computation time while ensuring a good accuracy of simulation results.

O2-65 Application of adaptive mesh refinement to evaluation of normal propagation zone in HTS Roebel cables

Pawel Lasek, Krzysztof Habelok and Mariusz Stepien
Silesian University of Technology, Poland

In order to evaluate normal propagation zone velocity (NPZV) in type II superconductors which are made as multi-layered tape structures it is necessary to make such calculation with finite element method (FEM). The complexity of problem increases when it comes to multi-strand cables such as Roebel cable where quench could propagate from strand to strand.

Dynamic wave-like nature of normal zone propagation often requires fine mesh in whole region of interest which leads to high computational complexity and longer time of evaluation. The high density mesh is needed in order to catch all the phenomena occurring at the wavefront of NPZ where calculation of electromagnetic and thermal quantities are changing dynamically, nonlinearly, with high frequency components.

Adaptive mesh refinement (AMR) assures high density mesh in localized regions, where computational power is needed and keeps sparse grid in regions where stable state has already been reached. This method allows improvement in computational time and power.

Application of AMR had been done with MATLAB software. The mesh grid consists of square finite elements, therefore there is no dedicated algorithm build into MATLAB to solve such described FEM problems. It only consists of script to solve for triangular and tetrahedral meshes. The research consisted also on making code and algorithm to create solver algorithm suited for AMR.

The considered Roebell cable is straight, 5mm wide YBCO tape with 10 strands. It is assumed that cable is operating at liquid nitrogen temperature (77K) and quench is initiated by thermal disturbance (i.e. due to friction) in one of the tapes.

O2-67 Modelling of local transition phenomena and their propagation in Rare-EarthBaCuO magnets to define effective detection thresholds and protection schemes

Arnaud Badel[1], Blandine Rozier[2], Tara Benkel[2], Brahim Ramdane[2], Gérard Meunier[1] and Pascal Tixador[2]
[1]CNRS, France, [2]University Grenoble Alpes, France

Rare-Earth BaCuO High Temperature Superconductors are an attractive option for very high field magnets due to their high engineering current densities up to very high magnetic fields when operating close to 4.2 K,

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combined with their high mechanical strength. However, REBCO tapes available today in hundreds of meters display inhomogeneities in performance along their lengths, with mm-scale variations of the local critical current by 10 to 20 % when measured at 77 K in self-field conditions. These inhomogeneities, combined with the very good thermal stability of REBCO tapes leads to a high risk of damaging hot spots when operating close to the estimated critical current, as in that case the critical current may in fact very well be overstepped locally. Detecting such local dissipation early enough to protect the magnet is difficult because the dissipating voltage stays very small and does not increase much. It is not also not obvious what threshold value such detection system should be set to to guarantee a safe discharge of the magnet.
The aim of our model is to study the influence of local critical current (Ic) inhomogeneities along the length of the conductor on local dissipative state occurrence and propagation, in order to validate protection scheme and detection threshold for practical magnets.
Our approach is electro-thermal only, to obtain models with manageable degrees of freedom even considering a whole application. A similar approach was already conducted for modelling Resistive-type Fault Current Limiter, but is generalized here for the case of superconducting coils.
The electric part is a circuit in which the conductor is discretized in 1D, its length divided into blocks along its length. The discretization can be varied at from mm-scale to cm-scale depending on the available critical current data on the conductor being used. The blocks are connected in series. The rest of the electrical circuit can include voltage or current sources, switches, discharge resistors, coupled inductances an so on. The local Ic in a coil depends not only on the tape inhomogeneities, usually characterized at 77 K self field, but also on the local operation conditions: the temperature, the magnetic field amplitude and its orientation. The influence of these parameters is included by multiplying the Ic 77K self field of each block by a local lift factor, whose value in every place of the magnet is evaluated thanks to in-field short sample characterization of the tape. The temperature is evaluated in the thermal model, the effect of the local magnetic field distribution and its time variation is also considered and will be discussed in another contribution.
Each block in the electric model is represented by two resistances in parallel, one for the superconducting layer with a power law behaviour and one for the normal layers. The current sharing is then computed, enabling the calculation of the Joule losses in every block.
The thermal model in general is three-dimensional and represent the coil geometry. In the case presented here the coil is pancake-based, the problem is then reduced to 2D and shows the pancake from above. Every turns are modelled, the thermal properties of the tape layers being averaged. Finite Element Method (FEM) is used to solve the transient non-linear thermal problem with adaptive time-steps. The tape discretization in blocks from the electrical model defines heat sources positions and size. Joule heating evaluated at a given time step is used to calculate the temperature distribution inside the domain at the next step. The average temperature on each block being used in turn as an input for the electrical model's next step, as both linear and non-linear electrical conductivities are temperature-dependent.
The use of that model to reproduce the quench event of a full-size REBCO high field insert will be taken as an example.

15:45 – 16:15 **Coffee Break**

16:15 – 18:15

Oral 3.1 – Bulks and Hybrid Structures & Miscellaneous I

Chairs:
Wescley de Sousa, Karlsrhue Institute of Technology, Germany
Benoît Vanderheyden, University of Liège, Belgium

O3.1-46
INVITED

Verification of Lorentz force velocimetry using a bulk HTS magnet system

Oleksii Vakaliuk[1], Bernd Halbedel[1] and Mark Ainslie[2]
[1]Technische Universität Ilmenau Institute of Materials Engineering, Germany, [2]2Bulk Superconductivity Group, Department of Engineering, University of Cambridge, United Kingdom

Lorentz Force Velocimetry (LFV), a novel contactless measuring technique, was demonstrated in [1, 2], where salt water was used to represent a weakly-conducting and slow-flowing fluid. The LFV working principle relies on measuring the Lorentz force that is generated due to the interaction of a magnetic field and moving, electrically conducting media. Equation (1) shows the scaling law of the Lorentz force that depends linearly on the electrical conductivity (σ) and mean flow velocity (u), and on the magnetic flux density squared (B2):
FL ~ σ·u B2 (1)
By measuring the reaction force induced for a prescribed magnetic flux density, it is possible to estimate the mean flow velocity of the fluid when the value of its electrical conductivity is known. LFV allows for a contactless measurement technique, which is particularly advantageous for aggressive media, e.g., glass melts. However, a reliable velocity determination in such opaque fluids requires high field generation, which cannot be achieved with conventional permanent magnets. Furthermore, precise force measurements—an integral part of LVF—place strict limitations on the magnet mass in the system. Hence, bulk high-temperature

superconductors (HTS), acting as strong trapped field magnets, are a promising technology to integrate into LFV [3].

This work reports experimental LFV measurements, where a magnetic field is generated by a bulk HTS magnet system (MS). The bulk HTS MS design, as well as the route for activation of the bulks as trapped field magnets, including cooling and magnetization, are discussed. The obtained data are used to verify a numerical model developed in COMSOL Multiphysics to predict and optimize LFV performance through numerical simulation. The numerical model is implemented as a fully 3D model using COMSOL's AC/DC module, where the bulk HTS pair is assumed to be fully magnetized with an appropriate constant Jc flowing through the cross-section of each bulk to reproduce measured trapped field profiles [4]. A velocity (Lorentz term, where $J = \sigma(E + v \times B)$ is then prescribed for a copper rod moving between the bulk pair, reflecting the experimental setup and conditions, which then allows the Lorentz force to be calculated.

The experimental and numerical simulation results agree well, exhibiting the linear relationship between the force and product of the electrical conductivity and velocity. Remarkably, the potential of generating very high magnetic fields using bulk HTS, tailored with precise force measurements, and highlights the prospect of applying LFV to weakly-conducting and slow-flowing fluids.

References:

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[3] O. Vakaliuk et al. Proceedings of International Union for Electricity Application, 2017. Hannover, 2017
[4] M. Ainslie et al., IEEE Trans. Appl. Supercond., V.28, No. 4, p.6800207, (2018)

Acknowledgement:

The authors M. Sc Oleksii Vakaliuk and Dr. Bernd Halbedel acknowledge the German Research Foundation (DFG) within the Research Training Group "Lorentz Force Velocimetry and Lorentz Force Eddy Current Testing" (RTG-1567/3) for the financial support. Dr Mark Ainslie would like to acknowledge the support of an Engineering and Physical Sciences Research Council (EPSRC) Early Career Fellowship EP/P020313/1

O3.1-34 Numerical modeling reveals the physical origination of HTS flux pump

Wei Wang[1] and Tim Coombs[2]
[1]Sichuan University, China, [2]University of Cambridge, United Kingdom

In this work, we reveal the physical origination of HTS flux pump based on numerical simulation with finite element method (FEM). The FEM model was established based on solid experiments of two types of circular-type magnetic flux pump devices (Appl.Phys.Lett. 110, 072601, 2017; Appl.Phys.Lett. 104, 032602, 2014). From the model, we show how the magnetic flux was transported inside the YBCO layer, with the help of applied magnetic poles, thus, reveal a novel electromagnetic phenomenon which explains the physical origination of HTS flux pump. We have also investigated the impact of magnetic wavelength on the magnetization, observing the magnetization evolves from classic model to novel results. In the end, we discuss the importance of several factors which affect the efficiency of flux pumping, an updated flux pumping experiment was performed to verify the solidity of our theoretical explanation.

O3.1-47 Passive magnetic shielding by machinable MgB_2: measurements and numerical simulations

Laura Gozzelino[1,2], Roberto Gerbaldo[1,2], Gianluca Ghigo[1,2], Francesco Laviano[1,2], Daniele Torsello[1,2], Valentina Bonino[3], Marco Truccato[2,3], Mihail Burdusel[4], Mihai A. Grigoroscuta[4,5], Dan Batalu[5], Gheorghe Aldica[4] and Petre Badica[4]
[1]Politecnico di Torino, Department of Applied Science and Technology, Italy, [2]INFN Sezione di Torino, Italy, [3]Università di Torino, Department of Physics, Italy, [4]National Institute of Materials Physics, Romania, [5]University Politehnica of Bucharest, Romania

The ability to shield an external magnetic field or to generate a permanent magnetic field are among the superconducting bulk applications that have attracted remarkable interest in the last years [1, 2]. In this framework, MgB_2 bulks are a promising solution due to their more homogeneous Jc distribution compared to (RE)BCO bulks [3], provided that the growing technique allows manufacturing suitably shaped products and the numerical modelling can be exploited to guide the devices' design.

In this work we investigated the shielding properties of an MgB_2 tube produced via an innovative technique that allows obtaining fully machinable MgB_2 bulks [4], thus able to be shaped as required by specific applications. This study involved both experimental characterizations and numerical simulations.

In more detail, the tube was fabricated starting from commercial Mg powders mixed with hexagonal BN, then spark plasma sintering was applied to produce a cylinder with an average relative density of 91%, height of 18.7 mm and radius of 10 mm. Finally, after a suitable process that makes the sample machinable, the cylinder was firstly drilled using bits with different radii and then turned on a lathe. The inner radius and the height of the final product are 7 and 17.5 mm, respectively.

The shielding properties of the tube were measured as a function of temperature and applied magnetic field both in axial and in transverse field configuration using cryogenic Hall probes [5]. Despite the height/outer

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radius aspect ratio is only 1.75, which makes the magnetic flux penetration from the tube edge not negligible, a shielding factor higher than 55 was achieved in the center of the tube at T = 20 K, when the external field m0Happl = 1 T was applied parallel to the tube's axis. A shielding factor higher than 2.5 was also measured in the transverse geometry, at the same working conditions.
After that, we reproduced the experimental results by finite element calculations. This required the development of an iterative process that, starting from the approach described in [6], allowed us to reconstruct the current density dependence on magnetic field. The induction field calculations were carried out using the vector potential formalism, with the approach addressed in [7], which has already successfully been applied in another study on MgB_2 and hybrid superconducting/ferromagnetic systems [8]. The modelling results well reproduced the experimental results as a function of the applied field, temperature and position along the tube's axis.
Finally, the same numerical model has been applied to design more efficient shielding systems, both modifying the shape of the MgB_2 bulk and adding ferromagnetic structures while the height/outer radius aspect ratio is kept almost unchanged. This activity is still in progress.

Acknowledgements:
Romanian team acknowledges MCI-UEFISCDI, grant POC 37_697 no. 28/01.09.2016 REBMAT and Core Program 2017/2018.
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O3.1-52 Hybrid analytical and integral methods for simulating HTS materials under various applied magnetic field configurations

Kévin Berger[1], Loïc Quéval[2], Frédéric Trillaud[3], Guillaume Escamez[4], Brahim Ramdane[4], Guillaume Dilasser[5], Hocine Menana[1] and Jean Lévêque[1]
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High Temperature Superconductors (HTS) are promising for applications requiring high power densities, such as superconducting electrical motors. Various approaches have been developed to model HTS, in particular for AC losses evaluation in thin wires and tapes. Indeed, AC losses are one of the key factors to size properly the cryogenic systems. In some applications, where the HTS materials are used as magnetic screens or as permanent magnets, such as in electrical motors, it is relevant to estimate properly the penetration of the magnetic field in order to optimize the magnetization processes and the integration of these materials in such systems.
In previous works [1]–[3], analytical tools in 2D have been successfully developed for calculating the magnetic field distribution in different devices integrating HTS bulks by considering them as perfect diamagnetic materials, e.g. a superconducting electrical machine or an inductor with an iron core used for the pulsed field magnetization of a bulk HTS. These methods provide continuous derivatives and are useful tools for the design and optimization of such systems. They lead to meaningful solutions with helpful physical insights. However, they are limited to simple geometries and do not take into account either eddy currents or the variation of the critical current density with the magnetic field, which is crucial in HTS. On the other hand, rapid modeling approaches are needed, and the use of classical numerical tools is often ineffective in the design and optimization process due to considerable calculation time. Specific numerical approaches ensuring a better compromise between precision and calculation time are still required.
In this context, the present work presents a hybrid model in which the HTS behavior is represented by the power law E(J,B) = Ec.(J/Jc(B))^n(B), taking into account the variation of the critical current density and the power exponent with respect to the magnetic flux density. The magnetic vector potential, the magnetic field and the current density distributions are computed by means of analytical and integral equations implemented on MATLAB. The resolution of the obtained stiff ordinary differential equations are performed using available solvers in MATLAB with adaptive time steps. The integral equations used to calculate the induced currents in the HTS materials are based on the well-known "Brandt method" developed in 1996 for strips and slabs, and later for disks and cylinders in an axial magnetic field.

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One of the main advantage of the hybrid method proposed here is that only the active parts are discretized. Distributions of the magnetic field over time and other quantities such as losses are presented. Calculation times for the studied problems are given and compared with those obtained from classical FEM software.

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O3.1-57 Computational fluid dynamics approach to determine current distribution in cylindrical bulk HTS

Toshiteru Kii
Kyoto University, Japan

Analysis of magnetization characteristics of bulk HTS is important for developing various applications. In this work, we introduce a computational fluid dynamics (CFD) approach to determine current distribution in bulk HTS.
At steady state, shielding current excited in superconductor can be regarded as moving Cooper pairs which have barycentric velocity. Its speed is very slow and density does not changes. Accordingly the moving Cooper pairs can be regarded as incompressible fluid.
In order to apply a particle method in CFD approach, circular current loops in a cylindrical bulk HTS are treated as ring particle, and the balance of force among ring particles are considered. In this work, (1) treatment of Ampère's force and movement of ring particles in the Particle-and-Force Method [1] are described, and (2) treatment of "pressure" and "velocity" of ring particle, in the Moving Particle Semi-implicit method [2] will be discussed.

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O3.1-72 Electromagnetic Lumped Parameter Model of High-Temperature Superconductors (HTS) Bulks in Magnetic circuits

João Fernandes and Paulo Branco
Instituto Superior Técnico - Universidade de Lisboa, Portugal

In this paper, an electromagnetic lumped parameter model is developed for high-temperature superconductors (HTS) bulks, to estimate the HTS magnetization levels when incorporated in a magnetic circuit. The simplification of representing ZFC HTS as perfect a magnetic shield or Field Cooling (FC) HTS as permanent magnets with an associated magnetic permeability may not result in the sufficient accuracy for the estimation of magnetic forces or electromagnetic parameters of one specific application.
The proposed model consists in dividing the HTS bulks into several homogeneous segments of different electric and magnetic proprieties. This division is not static but depends on the applied magnetic field. The model is based on the solutions of the magnetization of type-II superconductors in Kim model done in [2] to estimate the penetration of magnetic field inside the HTS bulk. To obtain a simple analytical solution, the work in [2] neglects the effect of the electric field inside the HTS bulk. Due to this simplification, its accuracy tends to decrease for very fast transients or pulses of magnetic fields. However, with it, it is possible to create the proposed lumped parameter model with the simple and sufficiently accurate representation of HTS bulks inside magnetic circuits.
The authors use for experimental validation, one magnetic circuit developed in [1] and [3] used for the magnetization process of YBCO and GdBCO HTS bulks with magnetic pulses. The magnetic circuit consists in two "E" shaped magnetic cores of electrical steel and faced to each other: one with a source coil for the application of the magnetic pulse, and the other with an air-gap for the insertion of the HTS bulk material. For the range of magnetic pulse amplitudes and times performed in previous works [1] and [3], the lumped parameter model is capable of predicting the magnetization levels of the trapped field after the magnetic pulse with good accuracy.

This model has particular interest for pre-designs of electrical machines or for the magnetization process of HTS bulks [1], due to its possible analytical solutions. With analytical solutions, one can use optimization tools, as genetic algorithms, to estimate the range of performances of the devices or the magnetization levels of the HTS.
In this context, with the help of experimental tests and finite element analysis tools (FEA), the accuracy of the lumped parameter results will be analyzed for different magnetic transients. The accuracy of the model will also be tested for different transient time intervals and pulse shapes. An experimental set-up for the magnetization process of HTS bulks inside magnetic circuit will be used for validation.
In future works, this model will be used with optimization tools to optimize the magnetization process of HTS bulks.
The main objectives of this research were:
- The development of an electromagnetic lumped parameter model for HTS bulks;
- The analysis of its accuracy for different magnetic transients;
- Its validation using experimental results from the magnetization process of HTS bulks incorporated in magnetic circuits.

This work was supported by FCT, through IDMEC, under LAETA, Project UID/EMS/50022/2013 and under Project PTDC/EEEI-EEL/4693/2014 – HTSISTELEC.

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18:15 – 20:00 **Social Event: Portuguese “*Arraial*”**

THURSDAY, 28 JUNE 2018

08:45 – 09:45

Plenary 2

Chairs:
Mário Ventim Neves, FCT NOVA, Portugal

The open source parallel multiphysics finite element library FEMPAR and its application to HTS

Prof. Santiago Badia
Universitat Politècnica de Catalunya – BarcelonaTech (UPC), Catalonia, Spain

In this talk I will provide an overview of an advanced scientific computing library, FEMPAR, which was developed from inception for being able to exploit supercomputers and ease the implementation of multiphysics solvers.
I will introduce the main showstoppers in scientific computing for the large scale implementation of complex phenomena, e.g., the CAD/CAE interaction and the efficient solution of (non)linear systems of equations in parallel. For every one of these problems, I will discuss our approach to improve the current situation.
It will involve the introduction of embedded methods based on unfitted finite element spaces, the use of octree background meshes, or the design of scalable multilevel domain decomposition algorithms. In the second part of the presentation, I will discuss applications of the library to some of the problems we are considering now, e.g., nuclear waste deep repository simulations, breeding blankets in fusion reactors, etc.
I will put special emphasis on the simulation of high temperature superconductors. This problem is very challenging since it involves curl-conforming (i.e., edge) finite elements, a very stiff nonlinearity, and the potential interest to couple different phenomena (thermal, electromagnetic, and solid mechanics problems). The development of highly scalable solvers for HTS is certainly complicated, and I will provide our experience in the field and our current approach.

Invited Talk: AC Losses

09:45 – 10:15

Chairs:
Francesco Grilli, Karlsruhe Institute of Technology, Germany

O-22

Progress of Large-Scale and Fast Electromagnetic Field Analyses of Coils Wound with Coated Conductors for Ac Loss and Shielding Current Calculations

Naoyuki Amemiya[1], Naoki Tominaga[1], Takeshi Mifune[1], Yusuke Sogabe[1], Yudai Mizobata[1], Masahiro Yasunaga[1], Akihiro Ida[2] and Takeshi Iwashita[3]
[1]Kyoto University, Japan, [2]The University of Tokyo, Japan, [3]Hokkaido University, Japan

We have been carrying out the electromagnetic field analyses of the coils wound with coated conductors by using the governing equation which is formulated with the current vector potential T. We apply the thin strip approximation, with which we can reduce the number of meshes remarkably by not dividing superconductor layer along its thickness, but it is still very challenging to perform the electromagnetic field analyses of the coils with complicated three-dimensional structures.
We report our recent progress of large-scale and fast electromagnetic field analyses of coils wound with coated conductors. Our challenge focused on the following three points: the reduction of required memory space which enables us the computations of large-scale models with reasonable computation time and memory consumption; the improvement of the efficiency of solving nonlinear equations originating from the nonlinear conductivity of superconductors; the robustness of the analyses of multifilament coated conductors with/without copper terminals, in which the conductivities of materials vary incomparably.
At first, we tried to improve the efficiency of solving nonlinear equations simply by the application of the Newton Raphson method instead of the successive substitution method. By applying the Newton Raphson method, the number of nonlinear iteration could be reduced, but, the entire computation time could not be reduced, even increased, because of the deteriorated convergence of the iterative solver of linear equations. The entire efficiency was improved successfully by combining the algebraic multigrid (AMG) preconditioning with the Newton Raphson method. Furthermore, the convergence of linear-equation solver in the analyses of multifilament coated conductors was improved dramatically by using AMG preconditioning, and, as the consequence, the robustness of such analyses was improved remarkably. Finally, we applied H-matrices, in which low-rank approximations are applied to submatrices of a dense matrix originating from the T-formulation, in order to reduce the required memory space and computation time.
As the outcomes of the challenge to the three focused points, we succeeded the analyses of the following coils for ac loss and shielding current calculations.
1) Saddle-shape coils of a cosine-theta dipole magnet for a carbon rotating gantry: the degree of freedom of the model was more than 1.5 million; the memory consumption by H-matrices was 177 GB, while that by a dense matrix had been 16.7 TB; the computation time was 78 hours by 56 parallel processes
2) Single pancake coils wound with multifilament as well as monofilament coated conductors: their spiral geometries were considered, and the results were compared with experiments; the degree of freedom of the model was around 0.37 million; the memory consumption by H-matrices was 20.3 GB, while that by a dense matrix had been 1.02 TB; the computation time was 6–8 hours by 16 parallel processes
3) Double pancake and layer-wound solenoid coils wound with multifilament coated conductors: their spiral and helical geometries as well as the copper terminals were considered; the degree of freedom of the model was around 0.4 million; the memory consumption by H-matrices was 35–39 GB, while that by a dense matrix had been 1.3–1.4 TB; the computation time was 20–25 hours by 16 parallel processes
4) The coils of a superferric magnet for a rapid cycling synchrotron: the degree of freedom of the model was around 1.1 million; the memory consumption by H-matrices was 330 GB, while that by a dense matrix had been 9.29 TB; the computation time was 151 hours by 56 parallel processes
All computations were done with Xeon E5 2667v4 and/or Xeon Gold 6136. We used the Intel Fortran Compiler 2018 and the Intel MPI library 2018.
This work was supported in part by the JSPS under KAKENHI 16H02326, by MEXT under the Innovative Nuclear Research and Development Program, and by JST under the S-Innovation Program.

10:15 – 10:45 Coffee Break

Oral 3.2 – AC Losses & Miscellaneous II

10:45 – 12:45

Chairs:
Naoyuki Amemiya, Kyoto University, Japan

O3.2-68
INVITED

AC loss computation of a dry-cooled MgB_2 SMES coil

Antonio Morandi, Umberto Melaccio and Pier Luigi Ribani
University of Bologna, Italy

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A three-year research project, called DRYSMES4GRID, has been funded by the Italian Minister of Economic Development. The project is aimed to demonstrate the feasibility of cost-competitive SMES based on Magnesium Diboride (MgB_2) with a cryogen-free cooling by means of the manufacturing and the testing of a demonstrator with an objective rating of 500 kJ/200 kW. The design of the SMES coil has been completed at the University of Bologna in collaboration with ICAS (Italian Consortium for Applied Superconductivity).
The calculation of AC loss of the dry-cooled MgB_2 coil during actual SMES charge/discharge operation is discussed in this contribution. The coil is made of a multifilamentary twisted MgB_2 tape with a copper strip added for quench protection. The THELMA model is used for the calculation. This in essence is a quasi-3D model assuming piecewise linear current density in the SC filaments along the longitudinal direction and allowing coupling currents to circulate, via the matrix metal, between the filaments and between the filaments and the stabilizing copper. A uniform current density is assumed in transversal cross section of the filament. The solving system is obtained by subdividing the conductor in a number of segments along the longitudinal direction and by assuming a 2D discretization of the cross section of each segment. With this approach a large number of turns, involving several layers of coil, can be considered in the numerical model. Calculated losses are made by the sum of the loss occurring in the matrix material, the copper and the superconductor and are obtained by integrating the dot product of E and J over the relative volumes. With regard to the loss occurring in the superconductor, a post processing approach is used for calculating a more refined value, thus avoiding possible inaccuracy due to assumptions of piecewise uniform current density in the filaments. In practice, the transport current and applied field of all filaments in one longitudinal segment are first calculated by means of the THELMA model and a 3D calculation of loss of each filament is then performed, thus taking into account the effect of current distribution within the filament.
Details of the model as well as practical results regarding the total AC loss of the SMES coil are discussed. Comparison is made with results obtained with the true 2D approach usually used for calculating the loss of coils. Comparison of computed AC loss of the coil with additional electromagnetic losses occurring in the metallic parts of the system (e.g. thermal shields, copper plates or braids for the thermal connection of the coil with the cryocoolers), calculated by means of commercial finite element codes, is also discussed.

O3.2-11 Model, method and formulation - terms related to simulations studied in the context of an HTS AC-loss modeller

Antti Stenvall and Valtteri Lahtinen
Tampere University of Technology, Finland

Contemporary literature about superconductor modelling, especially on HTS AC-losses, is full of different author dependent meanings for the widely used modelling related terms such as model, method and formulation. Sometimes these are combined like H-formulation model, or H-formulation method - both sometimes appearing in the same paper. In situations like these it is up to a reader to think what do the authors really mean. Consequently, the interpretation of the paper might be very much reader dependent. Further, if a reader concludes that the (possible philosophical) fundamentals in the paper are wrong, how could she believe in the application? In this talk we dive into the words like model, method and formulation and present our interpretation of these terms. We take HTS AC-loss modelling for the application context.

O3.2-20 On the relation of simulations and experiments in the context of HTS AC losses

Valtteri Lahtinen and Antti Stenvall
Tampere University of Technology, Finland

Computer assisted modelling is an essential approach to design new devices. It speeds up the process from the initial idea to an actual device and saves resources by reducing the number of built prototypes. An inseparable part of the whole modelling process is the development of modelling approaches and numerical methods and comparing the predictions obtained via modelling to experimentally achieved results. It is commonplace to discuss e.g. the accuracy of modelling results or the validation of a model. Here, we interpret such statements and, trying to understand what is the perceived meaning of e.g. validation of a self-consistent model, we shed light on the relationship of measurements and models. The fundamental issue of the difference between the discrete and the continuous underlying, a relevant question is: What is modelling and how should we view the modelling results in relation to experiments? We present our view on understanding the relation between nature, human-made prototypes and computer simulations. In particular, we set our considerations in the familiar context of AC losses in high-temperature superconductors.

O3.2-24 Filamentary-Equivalent Domain Model for Fast Simulations of AC Transport Power Losses in First Generation High Temperature Superconducting Tapes

Alexander Petrov, James Pilgrim and Igor Golosnoy
University of Southampton, United Kingdom

Challenges, linked with FEM modelling of superconductors, include the long computational time required to simulate the small domains that Bi-2223 superconductors possess. To decrease that time, the model of AC

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transport power losses is achieved by homogenization technique via a "filamentary-equivalent domain" approach. In it, a single homogeneous domain with effective material properties is used to represent the superconducting material. Two methods of homogenization are considered, where the domain would have either the approximate shape of the multifilamentary region (MRM), or the area of superconductor in the tape's cross-section (SAM). In order to investigate their validity, four tapes from the literature are modelled in three configurations. Both methods can accurately predict the transport power losses of the majority of configurations while demonstrating fast computational times. However, only MRM modelled accurately the total power losses in an applied magnetic field due to its ability to correctly represent spacial distribution of current density within a realistic topology of conducting region. This makes MRM the more promising technique of the two.

O3.2-32 **Probing vortex pinning in HTS with acoustic waves**

Maxim Marchevsky and Sören Prestemon
Lawrence Berkeley National Laborator, United States of America

Vortex pinning in type-II superconductors leads to a mechanical coupling between flux lines and atomic lattice of the superconducting material. This implies that elasticity of pinned vortex matter couples to the net mechanical stiffness of a superconductor. Such effect can be potentially detected experimentally by monitoring elastic moduli of a superconducting sample in magnetic field while varying its flux pinning strength either thermally, or by applying a driving current. Ultrasonic methods have been employed in the past in a similar manner to study the elastic and pinning properties of the vortex lattice [1]. We investigate numerically a feasibility of acoustic detection of vortex depinning in practical superconductors such as HTS ReBCO tapes, and report our preliminary measurement results using a variant of the newly developed acoustic thermometry technique [2]. The prospects for ultrasonic monitoring of quench "margin", and in situ mapping of pinning strength degradation in practical HTS conductors and magnet coil windings will be discussed.

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12:45 – 13:45 **Lunch**

13:45 – 15:45 **Poster Session**

See page 27 for details

15:45 – 16:15 **Coffee Break**

16:15 – 18:15 **Oral 4 – Mechanical Aspects & Numerical Modelling**

Chairs:
Philippe Vanderbemden, University of Liège, Belgium
Archie Campbell, University of Cambridge, United Kingdom

O4-12 **Numerical modelling of mechanical stresses in bulk superconductor magnets with and without mechanical reinforcement**

Mark Ainslie[1], John Chaddock[1], Danny Huang[1], Hiroyuki Fujishiro[2], Keita Takahashi[2], John Durrell[1] and David Cardwell[1]
[1]University of Cambridge, United Kingdom, [2]Iwate University, Japan

Bulk superconductors, acting as trapped field magnets (TFMs), can trap magnetic fields of magnitude over ten times higher than the maximum field produced by conventional permanent magnets, which is limited practically to rather less than 2 T. It has been shown that (RE)BCO (where RE = rare earth or Y) bulk superconductors can trap fields greater than 17 T: the longstanding world record field generated in an arrangement of two bulk superconductors of 17.24 T at 29 K was recently exceeded by 17.6 T at 26 K. The trapped field capability of a bulk superconductor is strongly related to its critical current density, Jc(B, T), and it is certainly possible that with state-of-the-art material properties and sample sizes that trapped fields > 20 T are achievable. However, the large Lorentz forces, FL = J × B, that develop when magnetising the sample lead to large mechanical stresses that can result in mechanical failure, with unreinforced samples typically failing for magnetic fields greater than 7-9 T. To achieve trapped fields > 17 T, the samples were reinforced mechanically using resin impregnation and carbon-fibre wrapping and shrink-fit stainless steel.

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In this presentation, a 2D axisymmetric finite-element model based on the H-formulation, implemented in the commercial finite element software package, COMSOL Multiphysics, is used to analyse the mechanical stresses in bulk superconductor magnets with and without mechanical reinforcement. The modelling framework is extremely flexible to include various magnetisation processes and conditions and detailed electromagnetic, thermal and mechanical properties of the materials involved. It is shown how such models can be used to design and analyse appropriate mechanical reinforcement to achieve even higher trapped fields in bulk superconductor magnets.

O4-15 A mixed-dimensional delamination structural model for general laminated composites including REBCO coated conductors

Justin Schwartz
The Pennsylvania State University, United States of America

Rare Earth-Barium-Copper-Oxide (REBCO) coated conductors (CC) are promising candidates for high energy, high field and high temperature superconducting applications. In the case of epoxy-impregnated REBCO superconducting coils, however, excessive transverse stresses generated from winding, cooling, and Lorentz forces on the CC can cause delamination, resulting in reductions in the load-carrying capacity as well as significant degradation in the coil's critical current. In this study, a general mixed-dimensional finite element model (FEM) based on the cohesive zone model (CZM) is developed to analyze the stresses, strains, and delamination in laminated composites, and in particular in a REBCO CC as a case study. The mixed-dimensional method allows any number of laminated high-aspect-ratio thin layers of any thicknesses in a composite to be modeled as stacked two-dimensional (2D) surfaces, thus, resolving the meshing and computational challenges in modeling such composites with full three-dimensional (3D) FEM approaches. For the studied REBCO CC, the major constituent layers, namely the silver, REBCO, and buffer layers, are modeled as 2D surfaces while the relatively thick stabilizer and substrate are 3D layers. All adjacent layers, including the 2D surfaces and 3D layers, are coupled via spring equations under the CZM framework. The mixed-dimensional model performs simulations with much higher computational efficiency than a full-3D counterpart while maintaining sufficient accuracy. Results such as the stress distributions and delamination behavior of the constituent layers of CCs under different delamination initiation conditions are presented.

O4-25 Peridynamic simulation of crack propagation in bulk superconductors with an electromagnetic-thermal model

Yanyun Ru, Huadong Yong and Youhe Zhou
College of Civil Engineering and Mechanics, Lanzhou University, China

Bulk high temperature superconductors exhibit superior magnetic properties compared to the conventional permanent magnets. Since bulk superconductors contain many micro-defects which are formed during fabrication process, the crack propagation will appear as the forces exerted on the bulk due to the Lorentz force are larger. Meanwhile, the variation of external magnetic field generates a significant amount of heat may also cause fracture of the bulk superconductor. For the dynamic analyses of crack propagation, the peridynamic theory has a remarkable advantage which uses the integral equations to include discontinuities in the constitutive equation of motion. Therefore, the aim of the work presented here was to investigate the mechanical behaviors of bulk superconductor when subjected to the electromagnetic force and thermal expansion of loading. The process of crack propagation of bulk is simulated. A finite element model based on the H-formulation is used to solve the electromagnetic force and temperature changes in the bulk with or without defects. Then, the crack initiation and propagation path can be predicted with a two-dimensional state-based peridynamic theory. The numerical simulations show a strong local enhancement of the load at the crack tip, and the existence of cracks greatly increases the risk of damage of superconducting bulk. Thus, it is necessary to avoid the presence of cracks in the manufacturing process.

O4-26 Effect of contact resistance on the thermal and mechanical behaviors in the no-insulation coil

Huadong Yong, Donghui Liu and Youhe Zhou
College of Civil Engineering and Mechanics, Lanzhou University, China

Compared to the conventional insulated coil, no-insulation (NI) coil wound with high temperature thin tape has high thermal stability. It is well known that increasing the contact resistance can reduce the charging delay. In addition, the experimental results show that coil with large contact resistance still has effective self-protecting feature. However, the energy loss due to turn to turn contact resistance may cause the local temperature increase and affect the thermal and mechanical behaviors. In this work, we will solve the equivalent circuit axisymmetric model which is coupled with heat conduction equation, and the temperature and current distributions in the coil under thermal disturbance will be presented for different contact resistances. Based on the finite element method, the mechanical equilibrium equation will be solved, and

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stress and strain distributions are also obtained. By discussing the maximal temperature, stress and strain in the coil, the appropriate contact resistances for different coil structures can be determined.

O4-14 Improvements in modeling of HTS properties

Ekaterina Kurbatova
Moscow Power Engineering Institute, Russia

Methods of calculation of magnetic systems with HTS elements should consider the electrical properties of superconducting materials including transition effect between superconducting and normal states, the Meissner effect, appearance of screening currents, hysteresis, and anisotropy. For calculations, the critical state model and its modifications are usually used or the flux-flow and flux-creep model, which separates different types of conductivity of the superconductor. When $J \le J_c$ there is only the creep-effect - creep of vortices from the pinning points, if $J > J_c$ there are simultaneously creep effect and motion of fluxoid – the electrical resistance appears. To expand the capabilities of models for approximation of continuous averaged current distributions in a superconductor in this paper it is proposed to complement existing models. There are two basic components in the volume of HTS: the conduction current density or transport current J, and currents in the form of small local vortex structures, determined by the density of the magnetic moments - magnetization vectors M. Approximated combined model of electrical properties of HTS materials is represented as constitutive equations designed for calculating electromagnetic field of the magnetic systems with HTS elements.

The electrical resistivity of HTS is represented by a function of temperature, current density, and magnetic field strength $\rho(|H|,|J|,T)$. The model for the current density contains six parameters which should be identified during the experimental studies of the material.

The magnetization M is represented by density of the magnetic moments of a set of small elementary superconducting hollow thin-walled cylinders distributed in the volume of a superconductor. It is assumed that diameters of cylinders are much shorter than the length, and the linear current density in the wall is limited by critical value with a nonlinear dependence on the magnetic field strength and temperature. In a magnetic field, the magnetization is equal to the linear current density of currents induced in the wall of the cylinder. The magnetization vector is directed along the axis of the cylinder. The lines of the initial magnetization curve and the return lines of the M (H) dependence are the straight lines with a constant tilt angle 45°. The maximum values of the magnetization are limited by the critical magnetization function $M_c(T,H)$.

It is assumed that in a certain small volume of the superconductor there are sufficiently large number of superconducting elementary cylinders, the parameters of which obey the probabilistic distribution laws. These parameters include the form of the dependences of the critical magnetization on the magnetic field strength and temperature, and the spatial orientation of the elementary cylinders. Averaged over the volume magnetization properties of the superconducting material are expressed as the magnetization dependences on the magnetic field strength and determined by the probabilistic characteristics of elementary cylinders. Anisotropic properties of magnetization are simulated by rotation of axes of elementary cylinders. The report demonstrates the functional capabilities of the developed models, which are included in the software package for the calculation of electromagnetic systems with high-temperature superconductors. The method of spatial integral equations for currents and magnetization was used for calculations. The convergence of the iterative solution of the equations is ensured by the restriction of the solution search area. To verify the effectiveness of the developed models, the results of calculations and experimental studies of the magnetic induction distributions and force interactions in the laboratory model of magnetic systems with HTS elements were compared.

O4-49 Comparison of constitutive laws for modeling high-temperature superconductors

Frederic Sirois[1], Francesco Grilli[2] and Antonio Morandi[3]
[1]Polytechnique Montreal, Canada, [2]Karlsruhe Institute of Technology, Germany, [3]University of Bologna, Italy

This contribution investigates the conditions of use and the equivalenc e (when applicable) of various constitutive laws used to model the electromagnetic behavior of high temperature superconductors, namely: 1) two versions of the critical state model (CSM); 2) the power law model; and 3) a so-called ``percolation model". All these models can be used to represent the same superconducting material with some limit of accuracy. The CSM and the power law model are well known in the literature. The percolation model can be seen as a generalization of the power law model that includes also a CSM-like behavior at very low electric fields.

The investigation has been carried out for three types of operating conditions: i) the sudden application of a DC excitation; ii) a pure AC excitation; and iii) combined DC and AC excitations. The equivalence between the different constitutive laws is shown to be a function of the magnitude of the electric fields and of the time scales involved. In the DC case, long time scales and very small electric fields are predominant, thus the superconductor requires a model that is accurate at low electric fields, such as the percolation model. The losses then arise from the relaxation of the magnetic field in the sample.

THURSDAY

In the AC case, the power law and percolation models are nearly identical when considering power frequencies, so choosing the simpler power law model is fully acceptable in practice. In addition, the CSM coincidentally provides good predictions of the losses in the power frequency range.
In the DC+AC case, when time scales in the range of minutes to hours are considered, it is shown that AC losses dominate over relaxation losses, and the same conclusions as for the AC case apply.

18:15 – 20:00 **Social Event: Gala Dinner**
Announcement of the 2020 Workshop venue.

FRIDAY, 29 JUNE 2018

09:00 – 10:30 **Oral 5 – 3D Modelling**
Chairs:
Antti Stenvall, Tampere University of Technology, Finland

O5-39 INVITED

Multi-physics variational methods for magnet and power applications

Enric Pardo[1], Milan Kapolka[1], Francesco Grilli[2] and Thomas Reis[3]
[1]Institute of Electrical Engineering, Slovak Academy of Sciences, Slovakia, [2]Karlsruhe Institute of Technology, Germany, [3]OSWALD Elektromotoren GmbH, Germany

High-temperature superconductors are very promising for high-field magnets and power applications, such as electric propulsion motors for aviation, wind generators or transformers. Modelling these applications presents many challenges, such as the large number of degrees of freedom, 3 dimensional (3D) problems or multi-physics. Therefore, it is needed to develop fast numerical methods that enable multi-physics calculations. This contribution presents a numerical method based on variational principles that enables 3D electro-magnetic and electro-thermal modelling, including the interaction between non-linear magnetic materials. Comparing to previous works, we reduce the computation time complexity below N^2, being N the number of unknowns, with exponent close to 1. The method is also highly parallelized, being able to run in computer clusters. Apart from outlining the variational principles, this contribution presents several examples.

3D modelling is performed for magnetization and cross-field demagnetization of rectangular prisms. Electro-thermal modelling enables to design the optimum thermal stabilization of a REBCO tape for a resistive fault-current limiter. The interaction between superconductor and ferromagnetic material is tested for REBCO pancake coils with iron yoke. For more complex geometries such as motors, the variational method is able to calculate the AC loss in the superconducting stator by using as input magnetic field maps calculated with COMSOL computations.

Therefore, variational principles have been shown to be a competitive tool to model high-temperature superconducting applications. By the time of the HTS modelling workshop, open-source examples will be available for the community.

O5-07

3D quench modeling based on T-A formulation for (RE)Ba2Cu3Ox High Temperature Superconductors

Yawei Wang, Zixuan Zhu, Min Zhang and Weijia Yuan
University of Bath, United Kingdom

he 3D quench modelling of high temperature superconductor (RE)Ba2Cu3Ox (REBCO) is always challenging due to the problem of multiple-physics coupling, tremendous computation, hard meshing, and un-convergence. This paper is to develop 3D quench modelling of REBCO conductors based on a innovate T-A formulation method. In this model, the electromagnetic and thermal behaviour of the REBCO conductor are assumed to be uniform along the thickness direction. The thickness of the coated conductor is neglected and it is treated as a thin shell, so that the number of meshes is reduced significantly. Meanwhile, the 3D geometry of the model in other dimensions is kept. The T-formulation is based on variables, current vector potential T, and it applied on the shell only to calculate the current distribution. The A-formulation is based on variables, magnetic potential A, and its is applied on the whole 3D domain to calculate the magnetic field. A heat transfer model is applied on the conductor shell only to calculate the temperature distribution. The three models are coupled in a commercial finite element method (FEM) software, COMSOL Multiphysics, and they are solved simultaneously by time dependent solvers. The modelling method developed in this paper makes the 3D quench modeling of REBCO conductors practical, less computation, simple and extendable.
Two cases of hot-spot induced local quench are analyzed in this presentation: a conductor on round core (CORC) cable and a Robel cable. The quench propagation is studied, the temperature distribution and current sharing between tapes are analyzed. The minimum quench energy and normal zone propagation velocity are

discussed. The factors affecting the quench behaviors are studied: transport current, temperature, terminal soldering resistance, thickness and materials of stabilizer. Measurers will be proposed to prevent a sustainable quench.

O5-35 **Investigation of the magnetic shielding of semi-closed tubes in transverse field: 3D modelling and experiment**

Jean-François Fagnard, Philippe Vanderbemden, Laurent Wera and Benoît Vanderheyden
University of Liege, Belgium

This communication deals with the properties of bulk superconductors to be used as low-frequency passive magnetic shields. Unlike soft ferromagnetic materials which are limited by their saturation magnetization (e.g. typically 0.7 T for mumetal), superconductors can offer efficient magnetic shielding up to several teslas. This feature makes superconducting screens the ideal material to shield the stray field emanating from several superconducting applications in which increasingly high magnetic fields are used. In a superconducting material, the shielding effect arises from macroscopic shielding current loops flowing at the outer perimeter of the sample. This feature makes shielding properties highly sensitive to the presence of non-superconducting joints. Although remarkable shielding properties have been recently achieved using high-temperature superconductors of various kinds [1-3], one of the current problem is to assemble medium-size superconducting parts to obtain large superconducting volumes. In axisymmetric superconducting geometries subjected to an axial field, 2D modelling (either using finite element or the Brandt approach) can be used to understand important features of the shielding properties. When a finite-size superconductors are subjected to a transverse field, however, 3D modelling should be used. The aim of the present work is to understand how hollow, semi-closed superconductors can be combined to increase the shielding volume.
In this communication, 3D finite-element modelling with an A-phi formulation is used to investigate the shielding properties of hollow and semi-closed bulk superconducting tubes. The tube is closed by a superconducting element shaped like a disk, a cup, or another semi-closed tube that is concentric with the first. We also consider a situation in which the extremity of the tube wall is machined to half of its thickness so that a disk superconductor can fit inside the tube. In this configuration, the gap between the shield and its cap thus contains a 90° bend. The modelling is used to determine the distribution of magnetic shielding efficiency along the axis of the tube. Results in the open and semi-closed configurations are compared to experimental data obtained on Bi-based superconducting shields at 77 K, and point out a nice qualitative agreement with modelling data. The modelled data shed light of the penetration mechanisms in each case and indicate the significant improvement that can be expected when the joint between the tube and the cap is superconducting.

References:
[1] L. Gozzelino et al., J. Supercond. and Novel Magn. 30 (2017) 749–756
[2] L. Wéra et al., IEEE. Trans. Appl. Supercond. 27 (2017) 6800305
[3] P. T. Yang et al., Supercond. Sci. Technol. 30 (2017) 085003

FRIDAY

10:30 – 11:00 **Coffee Break**

09:45 – 10:15 **Oral 6 – High Field Magnets & Grid Applications**

Chairs:
Loïc Quéval, GeePs, CentraleSupélec, Univ. Paris-Saclay, France
Antonio Morandi, University of Bologna, Italy

O6-16 **Analysis of magnetization loss on a helically wound superconducting tape in a ramping magnetic field**

Yoichi Higashi and Yasunori Mawatari
National Institute of Advanced Industrial Science and Technologies (AIST), Japan

High temperature superconducting (HTS) YBa_2Cu_3O_7-δ coated conductor on round core (CORC) wire has been developed for the last decade [1,2]. The CORC wire is a promising candidate of a superconducting wire for an application to high field magnets. This is because a coated conductor can be wound on a former with a short twist pitch, and the CORC cable can be bent guided by a flexible former as well. Indeed, the CORC wire with the diameter of a few mm and the twist pitch of a few tens of mm is presently available commercially.
A possible candidate of the HTS tape wire application is the superconducting coil in the magnetic resonance imaging (MRI) instrument. Although low loss structured HTS tape cables such as twisted stack tape cables have yet to be applied to a MRI magnet, simulation studies questing for the suitable cable structure with low magnetization loss is desired.
In the present work, we suppose the excitation/demagnetization of a MRI magnet, and thus we address the magnetization loss in a ramping magnetic field to explore the possible application of the CORC cable to a MRI

magnet. Employing the thin sheet approximation [3], our recent analysis successfully demonstrates electromagnetic properties of a twisted tape wire [4]. With the same scheme at hand, we carried out the both two and three dimensional numerical simulations on the current distribution and the magnetization loss on a helically wound superconducting tape, which mimics a CORC wire. Consequently, we obtained consistent result on the current distribution on the tape surface between the 2D and 3D simulations. As in a twisted tape wire, the current loop on a superconducting helix with one pitch is divided into two small loops owing to helical winding of the tape wire. Magnetization loss per unit wire length is also expected to be smaller than that on a flat tape because the tape surface area interlinking across magnetic fluxes gets smaller in the case of the helical winding. On the basis of both 2D and 3D simulations together with the analytic approach from tightly or loosely twisted limit, we will present the detail of the electromagnetic response on a superconducting helix.

References:
[1] D. C. van der Laan, Supercond. Sci. Technol. 22, 065013 (2009).
[2] Jeremy D. Weiss et al., Supercond. Sci. Technol. 30, 014002 (2017).
[3] H. Zhang, M. Zhang and W. Yuan, Supercond. Sci. Technol. 30, 024005 (2017).
[4] Y. Higashi, H. Zhang and Y. Mawatari, unpublished.

O6-18 How to Computationally Determine the Maximum Stable Operation Current of an HTS magnet

Janne Ruuskanen[1], Antti Stenvall[1], Valtteri Lahtinen[1], Jeroen Van Nugteren[2], Glyn Kirby[2] and Jaakko Murtomäki[1]
[1]Tampere University of Technology, Finland, [2]CERN, Switzerland

The slanted E-I characteristics of high temperature superconductors cause an interesting issue on their use in magnets: the short-sample critical current is only an indicative property for the maximum current a magnet can be continuously operated with. This was especially visible in the experiments of the world's first Roebel cable based HTS dipole magnet prototype built and tested in CERN in 2017 where the thermal runaway developed very slowly in many cases. Consequently, the maximum stable operation current could be overstepped for a while and stable operation could be recovered by lowering the current below the maximum of the stable range again. It is non-trivial to quantitatively predict this behaviour from the critical current measurements which are based on arbitrarily selected electric field criterion for the critical current. To make more rigorous predictions, one needs to consider in detail the interplay of cooling and heating in a winding and link this to the E-I relation. This kind of modelling must be naturally based on mathematical foundations on the definition of maximum stable operation current. However, such foundations are not easy to replicate in modelling and one ends up on searching for the necessary and sufficient conditions to get a value that is close enough to the maximum stable operation current. This work presents a methodology to determine the set of feasible operation currents, bounded above by the maximum stable operation current, to arbitrary precision as well as studies its mathematical background. Insight to this problem comes from the Roebel cable based dipole magnet studied in CERN during 2017.

O6-37 A critical assessment of the issues in the thermal modeling of an HTS CroCo conductor for the EU DEMO TF coils

Andrea Zappatore[1], Walter Fietz[2], Reinhard Heller[2], Laura Savoldi[1], Michael Wolf[2] and Roberto Zanino[1]
[1]Politecnico di Torino, Italy, [2]Karlsruhe Institute of Technology, Germany

A novel high-temperature superconducting (HTS) conductor concept for future fusion magnets, based on the HTS CrossConductor (CroCo) idea, has been recently proposed by the Karlsruhe Institute of Technology (KIT) [1].
The conductor concept is arranged in a cable-in-conduit configuration according to a so-called 6-around-1 cabling pattern, i.e. 6 HTS CroCo macro-strands twisted around a round copper core embedded in a stainless steel jacket and cooled by supercritical helium at 4.5 K. The single HTS macro-strand is made by stacked and twisted REBCO tapes surrounded by a copper sheath. Other research laboratories, involved in the design of HTS conductors for fusion applications, are developing (and testing) similar conductor concepts, i.e. based on the idea of a reduced number of twisted and jacketed macro-strands. Although inspired by the low-temperature superconducting (LTS) cable-in-conduit conductor (CICC) for fusion applications, the resulting cross-section of the conductor is very different: first, the diameter of the single CroCo macro-strand (~ 10 mm) is much bigger than the LTS strand diameter (≤ 1 mm). Second, the superconducting material (tapes) is the (macroscopic) core of the macro-strand, which is in thermal contact, but segregated with respect to the copper, whereas in the LTS strand the superconducting filaments are embedded in the stabilizer matrix. Third, the wetted perimeter of the HTS macro-strands in the CICC (~ 0.2 m) is much smaller than that of the LTS strands (~ 3 m). The main implication is that significant temperature gradients could build up in the macro-strands.

The consequence is that the straightforward applicability of the well-established 1D thermal-hydraulic models used so far to predict or reproduce the performance of LTS conductors and coils, e.g., the 4C code [2], is not guaranteed for HTS (CroCo) conductors and deserves a dedicated analysis.
Here we present a first 3D thermal analysis of the HTS CroCo CICC, using the commercial software STAR-CCM+, and analyze steady states and transients obtained applying to the conductor different thermal drivers, representative of what could occur in fusion magnets, for instance in the EU DEMO TF coils. The results of a simplified 1D model of the HTS CICC using the 4C code are compared with those of the 3D model, showing in which cases the former could be unsuitable to reliably describe the behavior of the conductor, e.g., leading to the underestimation of the hot-spot temperature in the HTS by tens of K.

References:
[1] M. J. Wolf, et al., "HTS CroCo: A Stacked HTS Conductor Optimized for High Currents and Long-Length Production", IEEE Transactions on Applied Superconductivity, Vol. 26, no. 2, 6400106, March 2016
[2] L. Savoldi, et al., "The 4C code for the cryogenic circuit conductor and coil modeling in ITER", Cryogenics, Vol. 50, pp. 167-76, 2010

O6-40 Design of a Superconducting Magnet for Magnetic Density Separation

Jaap Kosse[1], Chao Zhou[1], Marc Dhallé[1], Gonçalo Tomás[1], Andries den Ouden[2], Peter Rem[3], Jaap Vandehoek[4], Gianni Grassi[5], Trevor Miller[6], Marcel Ter Brake1[1] and Herman ten Kate[1]
[1]University of Twente, Netherlands, [2]Radboud University, Netherlands, [3]University of Delft, Netherlands, [4]Urban Mining, Netherlands, [5]Columbus Superconductors SpA, Italy, [6]Sumitomo (SHI) Cryogenics Europe Ltd, United Kingdom

An optimized magnet design has been identified for a conduction-cooled MgB_2 Magnetic Density Separation (MDS) system. MDS is a novel recycling technology that allows the separation of non-magnetic materials in a ferrofluid stream that flows through a strong vertical field gradient.
The main challenge of this work is to find a design which minimizes the distance between the fluid bed and the magnet, necessitating a flat cryostat. This leads to a the conflicting requirement of mechanical sturdiness with minimized thermal cryostat losses. To this goal, the design extensively relied on multiphysics modeling. In COMSOL a suitable coil lay-out was identified using 3D electro-magnetic simulations. Next, a mechanical structure provides the winding pack with adequate cooling but can also handle the Lorentz forces. Using an iterative simulation process, the effects of pre-stressing the winding pack using bolts; of thermal stress resulting from cool-down to cryogenic temperatures; and of the Lorentz load and upwards force towards the ferrofluid upon excitation were taking into detailed account. Finally, the maximum voltage and hotspot temperature during a quench were calculated to be within safety limits. The simulations have successfully led to an completed design and the tendering- and construction phase of the magnet has begun.
This work is part of the research programme "Innovative Magnetic Density Separation for the optimal use of resources and energy" with project number P14-07, which is (partly) financed by the Netherlands Organisation for Scientific Research (NWO).

FRIDAY

O6-64 Simulation, Design of an Innovative Superconducting Transformer by Using Flux Transfer for Next-Generation Grid

Janos Arpad Kosa[1] and Istvan Vajda[2]
[1]Department of Electrical Engineering Faculty of Science and Technology University of Debrecen, Hungary, [2]Obuda University, Hungary

Introduction:
The main point of this paper is that we must do its utmost to decrease the short circuit current regarding high power electric energy system. Currently electrical power is growing hence the short circuit current is also increasing. The destructive effect is proportional with the squared of the short circuit current. We have to limit the short circuit current because the grid and devices will damage. Hence this paper is aimed at avoiding its destructive effect for the duration of conventional protection. Increasing power indicates the need of this creation of this simulation.
Objectives:
- The primary objective of this paper and presentation is to simulate and develop a novel superconducting transformer model that can be fitted to a modern energy system.
The purpose of our work will be to show a new direction for protection of next generation electric grid. The model will show the rapid change of the fault current, and this work gives opportunities of this device. The simulation results will show that our transformer can effectively limit short circuit current and improve the operation reliability of electric energy system.
- The second objective is the following: We will use the flux transfer theory regarding this work.
In previous work we presented this solution [1,2,3]. Our paper will show the simulation and calculation of the short circuit current in the applied superconducting wire.
Proof of concept by simulation:

The applied solution that we analyse has more advantages. These are the followings:
- The energy source gives lower power to the fault location during the operation of the applied conventional protection. Thus, the conventional protection (for example a circuit breaker) have to break lower short circuit current.
- Impedance of transformer by using flux transfer is higher. This requirement is for high power transformer in conventional system also.
These facts indicate to develop a novel construction of a transformer for high power energy system. We will give this simulation and results. Results of simulation will show the operation current and short circuit current of our self-limiting transformer.

References:
[1] Kosa, J., & Vajda, I. (2009). Transformation of the DC and AC Magnetic Field with Novel Application of the YBCO HTS ring. IEEE Transactions on Applied Superconductivity, 19(3), 2186-2189.
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[3] Kosa, J., & Vajda, I. (2012). Novel Application of the Perfect Closed Superconducting Loop Made of HTS Wire. In Materials Science Forum (Vol. 721, pp. 15-20). Trans Tech Publications.

O6-69 **Computing implementation of stabilized HTS tape model based on distribution of currents between the tape layers**

Alfredo Álvarez[1], Pilar Suárez[1], Belén Pérez[1] and João Murta-Pina[2]
[1]University of Extremadura, Spain, [2]UNINOVA/CTS Universidade NOVA de Lisboa (FCT NOVA), Portugal

In large scale applications of high-temperature superconductors (HTS) such as fault current limiters (SFCLs) or SMES, HTS tapes are often the simplest element involved in the design of such elements. In turn, those elements are part of wider environments, as power grids, which are analyzed by programs using models of well-known conventional electrical elements, e.g. resistances, reactors, transformers, switchers, etc. The problem of superconducting elements for been modelled as the other ones is the non-linearity of their response. This is due to the non-linearity of the superconducting tape which those elements are done with. In previous studies, we have proved the distribution of current between the layers of the stabilized HTS tape, and a model was developed with good agreement with measurements when the current in the tape is higher than the critical current Ic. In that model, the response of the superconducting layer is modelled by a variable resistance directly programed as a function of the current in the layer. In the work we present here, the response of the superconducting layer is adjusted by mean of hysteretical functions, closer than the theoretical models of superconductors. The model was adjusted from experimental measurement and the results and conclusions for straight tape, only with self-field, are presented here.

13:00 – 14:00 **Lunch**

14:00 – 16:00 **Ora 7 – Maglev & Bearings**

Chairs:
Guilherme Sotelo, Fluminense Federal University, Brazil
Mark Ainslie, University of Cambridge, United Kingdom

O7-33 **Simulations of REBCO Tapes Double Crossed Loops Coils with Integral Equations Method**

Flavio Martins[1], Felipe Sass[2] and Rubens de Andrade Junior[1]
[1]Universidade Federal do Rio de Janeiro, Brazil, [2]Universidade Federal Fluminense, Brazil

In superconducting passive magnetic bearings, stable levitation gaps are naturally achieved without interference of any control system. This property finds an application on urban transportation, as seen on the MagLev Cobra project. The superconducting magnetic bearing system used in this vehicle is composed by a rare-earth permanent magnet guideway and a set of cryostats containing YBCO bulks in liquid nitrogen under the vehicle. It is widely known that bulk superconductors lack an affordable, quality-standard large scale production process. This hampers the project to further advance into an industrialization status. On the other hand, REBCO tapes counts with large scale production by manufacturers worldwide and have long surpassed bulks in critical currents and pinning capacities, making them a possible substitute for YBCO bulks. Some research groups have already started developing this topic with stacked REBCO tapes.
An idea recently proposed is to use REBCO tape segments with partially opened slits forming superconducting jointless loops. When these loops are stacked side by side they become a coil. Two coils (one slightly smaller than the other) are assembled one inside the other to form a double crossed loops (DCL) coil. The advantage of these coils over simple stacks is their greater magnetic flux linkage area, allowing greater induced currents (and thus greater levitation forces).

This novel geometry is proposed to substitute the YBCO bulks inside the MagLev Cobra cryostats and become its next generation of magnetic bearings. In order to increase the (levitation force)/(tape length) ratio, simulation methods are employed and, in this work, the first results are demonstrated.
The simulation strategy adopted is of evaluating the induced currents and forces developed by a cross section of the coils when relative movement is imposed between them and the magnetic field from the guideway. The REBCO tapes are modeled as infinitely thin, one-dimensional segments, where the current density is written as an integral equation. This technique is referred as the Integral Equations Method. Critical current density is considered to have an elliptical dependency to parallel and normal to the tape plane magnetic flux density components ($J_c(B_\perp, B_\parallel)$).
The current paths in the DCL coil are not conventional ones, for they do not follow an axisymmetric distribution. To correctly represent its distribution, each current path must be modeled by a constraint, thus every tape should be represented on the simulation. So, it does not allow homogenization techniques, justifying the chosen approach. This technique also allows a more verisimilar representation of the tapes.
The main design parameters analyzed are number of loops, inner area width and distance between tapes (stacking factor). It was verified that these least two parameters greatly influence the levitation force, meaning that not only by stacking the most tapes in a given volume will maximize the levitation force. In fact, levitation force is inversely proportional to the stacking factor. However, the lesser the stacking factor, the greater the force hysteresis due to flux creep.
The interesting behaviors observed in the simulations shall be discussed. It should be noted that the studied geometry with such application is new in the literature, thus encouraging further investigation.

O7-54 Numerical Modeling for the Dynamic Characteristics of HTS Magnetic Levitation System

Wenjiao Yang[1], Changqing Ye[1], Kun Liu[1], Loïc Quéval[2], Gang Li[1], Tianyong Gong[1] and Guangtong Ma[1]
[1]Southwest Jiaotong University, China, [2]CentraleSupélec, France

With the merits of passive stability, energy-saved and environment-friendly, high-temperature superconductor (HTS) magnetic levitation (Maglev) is regarded as a promising candidate for the future transit. The ultimate goal of this paper is to build a numerical model to advance the understanding of the dynamic charactristics of HTS Maglev system for the potencial high-speed maglev vehicle applications, such as that of over 1000 km/h. Numerical modeling of HTS bulk to characterize its dynamic levitation performance over a permanent magnet guideway (PMG) is reviewed in this paper with emphasis on what has been done in our laboratory in the past decade. A three-Dimentional strongly coupled electromagnetic-thermo-mechanical model for simulating the dynamic characteristics of the HTS Maglev system is established. In this proposed model, the relative movement between HTS and PMG is achieved through indirect coupling with both numerically simulated and analytically calculated magnetic fields imposed on the HTS boundary. The comparison between the results from two methods underlines the merits and drawbacks of using analytical magnetic field. Confirming the accuracy of the model, the emphasis is placed on the study of dynamic behaviors of a freely levitated HTS body. The regular pattern of vibrational response under various amplitude, frequency and type imposed impulses, including levitation force, accelerated speed, displacements, is deeply explored. The dependence of the dynamic behaviors on the material properties of HTS is also addressed in this paper. The results will play a positive role to suggest the viable measures for improving the stability of the HTS Mag Lev system.

O7-56 Optimization methodology of race-track HTS magnets for transportations

Tianyong Gong, Guangtong Ma, Zhengwei Zhao, Kang Liu and Chao Wang
Southwest Jiaotong University, China

Optimization methodology of race-track HTS magnet to characterize its thrust or levitation performance when subjected to travelling or static magnetic fields is reported in this paper with emphasis on how to built the analytic models for calculating magnetic-field distribution and geometric optimization model of HTS magnet. The merits and drawbacks, of the proposed analytic models verified by a finite element model, to calculate the spatial magnetic field distribution of race-track HTS magnets are discussed in a three-dimensional scale. Then an optimization method that is shown to be efficient to fast search the optimal geometric parameters is introduced to help design the HTS magnets for the applications of linear motor or magnetic levitation. We make a highlight to describe these proposed analytical models, for finding out the most efficient one among them to calculate the self-field of the race-track magnet based on the magnetic flux density or the magnetic vector potential. Enabled by the efficiency and robustness of the vector potential method, we further incorporated this analytical model into finite element software with optimization function and developed an intelligent scheme for computing a linear motor and HTS levitation transportation system to realize an efficient design. Measurement equipment of a linear synchronous motor over 10-kN thrust capability has being established in our laboratory and the force properties of the linear motor will be tested to verify our optimization model.

FRIDAY

O7-58 Simulation of Stack-Type Superconducting Magnetic Bearings

Loïc Quéval[1], Kun Liu[2], Wenjiao Yang[2], Víctor M. R. Zermeño[3] and Guangtong Ma[2]
[1]GeePs, CentraleSupelec, University of Paris-Saclay, France, [2]ASCLab, State Key Laboratory of Traction Power, Southwest Jiaotong University, China, [3]Karlsruhe Institute of Technology, Germany

The use of stacks of high-temperature superconducting REBCO tapes has been recently extended to maglev technology [Sass2012, Sass2013, Pokrovskii2014]. This is to be compared with the traditional use of bulks for this kind of application [Wang2002, Schultz2005, Mattos2016]. Since then, considerable efforts have been made to characterize stack-type superconducting magnetic bearings [Sass2014, Patel2015, Osipov2016, Abin2016, Pokrovskii2016, Patel2016, Osipov2017, Patel2017]. Nevertheless there is still a large gap between laboratory-scale superconducting levitation and their practical use.
Numerical models could be of help here, allowing us to predict the performances of superconducting magnetic bearings and to optimize them [Queval2016a]. But if a variety of models have been successfully developed to simulate bulk-type superconducting magnetic bearings [Takeda1994, Tsuchimoto1994, Lu2008, Dias2009, Ma2010], the simulation of stack-type ones is still problematic. Indeed the anisotropy of REBCO stacks, due to the fact that the neighboring layers are electrically isolated, need to be taken into account. And if models work well for the simulation of a small number of tapes, their direct applicability to bearings involving hundreds of tapes leads quickly to prohibitive simulation time and memory requirement. In an effort to reduce the computing time, the anisotropic homogenization [Zermeno2013, Queval2016b] is a good method. But it should be used with caution, and the first validation proposed by Sass et al. [Sass2015] should be extended to other geometries and other test conditions.
This is the goal of this article. We use here two different H-formulation 2-D finite element models for simulating a bearing having 120 tapes. The first one considers all the tapes with their actual thickness. The second model uses an equivalent anisotropic homogeneous bulk. For the first time, the results of the two models are compared together and with experimental data for both levitation and guidance force. Difficulties and opportunities offered by each method are discussed in details, with a particular emphasize on optimization.

O7-71 Study of a Cylindrical Geometry Design for the ZFC-Maglev System

Francisco F. Silva and P. J. Costa Branco
IDMEC, Portugal

In this paper, a comparison is made between two types of geometries for the ZFC-Maglev: its actual rectangular HTS bulk geometry [1], and a novel cylindrical geometry, consisting of a cylindrical track with equally spaced permanent magnets, and bulk superconductors with the geometry of a half ring, levitating on the cylindrical track, with a constant radial air gap. The metric for comparison is the lateral stability and levitating forces of both geometries.
The studies presented in this paper are a continuity of previous research made [1][2] regarding the use of ZFC HTS for the design of a new magnetic levitating system, where a prototype of the rectangular geometry was developed. Previously studies regarding the levitating forces and lateral forces were made [1], as well as vertical and horizontal stability [2].
It was hypothesized that a cylindrical geometry would bring significant advantages over the original rectangular geometry. In this context, a design for a new cylindrical geometry was developed, and the experimental results of the lateral stability and guidance forces will be compared to the results of the 3D finite element method (FEM) simulations made with the full cylindrical geometry, the cylindrical ZFC-Maglev.
The main objectives of this research were:
- The experimental studies regarding the lateral stability response and guidance forces of the original rectangular geometry.
-The design of a new cylindrical geometry, using a FEM software, and calculation of the guidance forces and lateral stability response.

This work was supported by FCT, through IDMEC, under LAETA, Project UID/EMS/50022/2013 and under Project PTDC/EEEI-EEL/4693/2014 – HTSISTELEC.
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16:00 – 17:00 **Discussion, wrap-up and closing**

FRIDAY

POSTERS

THURSDAY, 28 JUNE 2018

13:45 – 15:45 **POSTER SESSION**
Chairs:

P-13 Reduced Basis Method for the electro-thermal behavior of an HTS commercial tape

Nicolo Riva[1], Bertrand Dutoit[1] and Francesco Grilli[2]
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In recent years, a growing interest into superconductor modeling for research, energy and transport applications led to the development of efficient numerical methods. The electro-thermal behavior of high-temperature superconductor (HTS) tapes is one of the most interesting and critical aspects; commercial and home-made software implementations are paving the way for the use of superconductor modeling.
However, the simulated quantities of interest (e.g. temperature) depend on the solution of parametric partial differential equations. The parameters, namely length or width of an HTS tape, thermal, electrical or mechanical properties of the tapes, can vary in a wide range. A sensitivity analysis for these parameters can therefore be computationally very demanding with those conventional software implementations. In this contribution, we discuss the possibility of using Reduced Order Models (ROM) to perform sensitivity analyses. These techniques enable accurate and rapid numerical simulations obtained by low-dimensional parametric models for various complex applications. In particular, we tried to apply a particular ROM (namely the Reduced Basis Method) to model the electro-thermal behavior of a commercial HTS tape. The results obtained with a Reduced Basis Method implemented in MatLab are compared in terms of accuracy and performance with those obtained with a conventional model implemented in COMSOL Multiphysics.

P-21 Comparison of 2D simulation models to estimate the critical current of a superconducting double pancake coil

Yingzhen Liu[1], Jing Ou[2], Fabian Schreiner[1], Shengnan Zou[1], Francesco Grilli[1], Mathias Noe[1] and Min Zhang[3]
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Large-scale direct-drive superconducting wind generators have been a research topic for years, because the superconducting generator enables higher torque density and efficiency, lower weight and smaller size. In the generator, the superconducting double pancake coils are used to generate the main flux density in the air gap, which is significantly important for the energy conversion. Correspondingly, the performance of the superconducting coils plays an essential role in determining the generator performance. However, the performance of the superconducting coil is limited by its critical current, which is determined by the magnitude and orientation of magnetic field inside the superconductors. Hence, in-depth investigations to estimate the critical current of the superconducting coils are necessary before manufacturing the coils. Available transient simulation models to estimate the critical current are through H-formulation and T-A formulation. Both methods consider the same ramping up process of the superconducting coil as the experiments and inhomogeneous current density distribution along the width of the superconductor. However, the computation time is longer than steady state models: P-model and homogeneously current-density model. To find the best way to calculate the critical current, the four methods are used to estimate the critical current of a double pancake superconducting coils and results are compared with the experiment. As a result, the homogeneously current-density model is recommended estimating the critical current of the superconducting coils for a superconducting generator.

P-27 Numerical analysis of behavior of HTS tape cooled by liquid nitrogen at current pulses more than critical current

Vasily Zubko, Sergey Fetisov and Sergey Zanegin
Russian Scientific R&D Cable Institute, Russia

Distinguishing feature behavior of HTS tape cooled by liquid nitrogen at current pulses more than critical current of the HTS tape together with extreme nonlinearity electrical conductivity of the superconductor also there is boiling hysteresis phenomenon in a nitrogen. A coupled thermal and electric numerical model was developed to analyses the behavior of the HTS tape in these conditions. The numerical model has well helped us to understand characteristics of the heat transfer from the HTS tapes to liquid nitrogen. Present paper describes a way to estimate the heat transfer coefficient during transition between natural convection and nucleate boiling and at nucleate boiling in liquid nitrogen using dates from measurements of behavior of the HTS tape cooled by liquid nitrogen at different current pulses.

P-28 Numerical simulation of the bending strain influence on the critical current and dynamic of the vortex structure in HTS conductors coated

Igor Rudnev, Anna Moroz, Anastasiya Maksimova and Vladimir Kashurnikov
National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Russia

The influence of the bending strain on the critical current density and voltage-current characteristics of HTS coated conductor have been studied by using Monte-Carlo method. We show a decrease in critical current density with the strain increasing. The change in E-J characteristics and critical current value were collated with dynamics of vortex structure in superconductor. It was found that the freezing and defreezing of the vortex lattice with a change of transport current result in step-like shape of E-J curves. Obtained results of numerical simulation are in a good agreement with the data of experimental research.

P-30 Effective Simulation of Normal Zone Propagation Velocity In YBCO Based ROEBEL Cable Using Adaptive Mesh

Luca Ferranti, Antti Stenvall, Valtteri Lahtinen, Tiina Salmi and Janne Ruuskanen
Tampere University of Technology, Finland

Normal zone propagation velocity (NZPV) is an important quantity used, e.g., in assessing if a magnet can be self-protectable. Using numerical methods, like Finite Elements Methods (FEM), for solving NZPV values with high accuracy can be time consuming due to the nature of the problem requiring dense mesh: the finer the mesh, the longer the simulation will take. The simulation time can be significantly reduced if an adaptive mesh, dense only where needed and sparse elsewhere, can be used. In the temperature distribution along the cable length, the temperature front, i.e. the region between the evolving normal zone and the non-quenched zone, has the greatest temperature gradient and therefore requires the densest mesh in order to obtain high accuracy in NZPV simulations. Beyond the front, where the cable has not quenched, the temperature is constant and therefore the mesh can be much sparser without loss of accuracy. The adaptive mesh can be combined with a front-tracking algorithm. By tracking the position of the front, one can determine the areas where denser mesh is needed. In this work, we propose different front-tracking based adaptive mesh implementations and compare their performances in predicting normal zone propagation velocities in the HTS Roebel cable.

P-31 Current Limiting and Magnetizing Characteristics Due to Winding Locations of SFCL using E-I Core

Tae-Hee Han[1], Shin-Won Lee[2], Seok-Cheol Ko[3] and Sung-Hun Lim[4]
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This paper compared current limiting characteristics of superconducting fault current limiter (SFCL) using E-I core due to the location of windings. Since E-I core has three legs and two magnetic paths, the current limiting characteristics of SFCL were expected to be affected by the installation location of windings, either center leg or right/left leg. To analyze its characteristics, the electrical equivalent circuit of the SFCL were derived and the electromagnetic analysis for the SFCL with the designed structure were performed. From the short-circuit tests, the hysteresis curve and the voltage-current trajectory of the SFCL due to the installation location of windings were extracted and compared each other.
The SFCL with windings in the center leg of E-I core was shown to be larger magnetizing inductance compared to the one with windings in the right or left leg of E-I, which was analyzed from the hysteresis curve. In addition, larger decreased fault current right after the fault occurrence in the SFCL with windings in the center leg of E-I core was confirmed than the SFCL with windings in the right or left leg of E-I.

P-36 Electro-thermal modelling for optimization of CC tape in DC fault current limiter

Fedor Gömöry[1], Marek Mošať[1], Enric Pardo[1], Michal Vojenčiak[1], Christian Lacroix[2] and Fréderic Sirois[2]
[1]Institute of Electrical Engineering, Slovak Academy of Sciences, Slovakia, [2]Department of Electrical Engineering, Polytechnique Montréal, Canada

Finite element modeling by Comsol Multiphysics is performed to analyze the process of quenching a coated conductor tape into resistive state by a pulse of DC voltage. Influence of various tape parameters (critical current, normal state resistivity, thermal capacity) on the maximum temperature experienced by superconducting layer is investigated. Recommendations for an optimization of tape suitable for a resitive Fault Current Limiter can be drawn from such study. Possibility to speed up the computations by using simplified representation of material parameters is discussed and some results of these efforts presented.

P-38 Numerical simulations of the penetration of magnetic field in a superconducting thin film: H-phi formulation with transformation-shell techniques

Loïc Burger, Christophe Geuzaine, François Henrotte and Benoît Vanderheyden
University of Liège, Department of Electrical Engineering and Computer Science, Belgium

We consider the Finite Element Method (FEM) to solve numerically the problem of the penetration of perpendicular magnetic field into a superconducting thin film. Although theoretical boundary conditions on electromagnetic fields are given at an infinite distance from sources, the FEM method applies boundary conditions at the surface of the mesh, and hence has to incorporate in the model a large volume of air outside the superconducting film. This not only represents an approximation with regard to the theoretical boundary conditions, but also increases the number of degrees of freedom and the computation time. The shell-transformation techniques [1] is an answer to this problem. It consists in enclosing the near-field FE model in a meshed shell region, and to map this shell region, which is of finite extension, onto the exterior of the FE model, which is of infinite extension. The shell region can have various shapes (e.g., hollow parallelepiped and hollow sphere in 3D), and the boundary condition can then be imposed on the outer surface of the shell with no approximation. We investigate the possibility to reduce the number of degrees of freedom with the help of the shell-transformation techniques, in the framework of an H-phi formulation. To this aim, we compare the number of degrees of freedom, the computational time and the accuracy of the solutions in two cases: (1) with a shell-transformation, and (2): without shell-transformation, in a large non-conducting domain. The obtained results are compared for different geometries (thin disk and thin strip in the critical state, square thin film). The influence of the order of the elements in the transformed region, the shape and size of the region where the shell-transformation is applied and the mesh quality inside this region are also considered.

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Acknowlegments:
This work is partially supported by the ARC grant 13/18-08 for Concerted Research Actions,
financed by the French Community of Belgium (Wallonia-Brussels Federation).

P-43 REBCO magnet mechanical modeling 101: The full workflow with insight to typical errors resulting from wrong stress values

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Thermal and electromagnetic dependence of REBCO materials, the composition of the REBCO wire layers and high aspect ratio of the REBCO wires poses demanding challenges for mechanical modelling of coils made out of such materials.
In this partially tutorial type of workflow we present typical steps for simulating mechanical behavior of superconducting magnets in ANSYS. As an example, we use a Roebel cable based REBCO accelerator dipole prototype. This presentation includes going through modelling assumptions for physics and modelling domain, coordinate systems, boundary and interface conditions, meshing and post-processing for results.
Additionally in the presentation, attention is drawn towards errors resulting from interpreting stress values from various types of models based on different modelling assumptions.

P-44 Multiphysical simulation of levitation bearings based on 2G HTS tapes

Irina Anischenko, Dmitriy Abin, Maksim Osipov, Sergei Pokrovskii and Igor Rudev
NRNU MEPHI, Russia

The reduction losses in the supports of fast rotating rotors and increasing their reliability are actual technical tasks. For kinetic energy storage devices (SMES) the technical characteristics of the support nodes determine the energy efficiency of the entire device, because it largely determines losses in the energy storage mode. Currently, mechanical and electromagnetic bearings are often used as the SMES support. The use of electromagnetic bearings based on high-temperature superconductors (HTS) allows to construct a non-contact magnetic flywheel suspension without friction. The development of mathematical modeling methods of magnetic systems with HTS elements is necessary for creation products with superconductors and new promising designs of HTS bearings which will correspond the increasing requirements for the characteristics of the magnetic suspension of SMES. These methods must take into account the complex features electrophysical properties of HTS materials. A deeper analysis of the existing designs of HTS is needed to explain the prospects of their application in high-speed rotor mechanisms.
In this paper we present the results of multiphysical modeling of several possible geometries of magnetic levitation bearings on HTS (disk, cylindrical and supporting bearings). The assembly of all simulated magnetic bearings includes the following modules - HTS blocks and permanent magnets blocks. Three possible configurations of the bearing's HTS block are considered: blocks of 2G HTS tapes stacks, HTS blocks with HTS rings, and 2G HTS pancake coils. For cylindrical and disk types of bearings it is supposed to cool the superconductor in the assembled state, i.e. transition to the superconducting state is carried out in the permanent magnets magnetic field (FC mode)
Separately, one can single out the calculations of the supporting type of the HTS bearing, which is intended primarily to compensate the gravity force. The stator of such a bearing is made of individual superconducting elements, usually disks, the rotor magnetic system is located opposite the HTS elements and consists of axially

magnetized permanent magnets or the Halbach array. For this construction type, the cooling of the superconductor is calculated both in an external magnetic field (FC mode) and outside the field (ZFC mode).
For all of above calculations, the cooling of superconducting elements is carried out by the cryocooler to temperatures in the range from 40 K to 80 K.
The magnetic bearings calculation were carried out using the Comsol Multiphysics software (modules: rotating machinery (RM), Partial Differential Equations (PDE), Heat Transfer in Solids (HT)) and includes a complex calculations of the electrophysical and thermal processes for the FC and ZFC cooling modes for the HTS elements cooling by the cryocooler (for several possible temperatures), the system mechanical loads calculations, the losses calculations of electrically conductive elements due to induced currents, and optimization of the parameters to ensure maximum efficiency of the bearings. The calculations are performed in 2D and 3D modes, the model takes into account the real geometric HTS tapes dimensions, as well as the features of the layered structure of the stacks (real tapes architecture).
The magnetization curves calculations, the interaction forces between the rotor and the stator, the calculations of losses in the system, and the analysis of effect of thermal processes on the levitation properties of the bearing cooling by the cryocooler in the FC and ZFC modes were carried out. Comparison with calculated characteristics for various configurations of the HTS bearings and with the experimental results were made, the advantages and disadvantages of each type of HTS bearings were shown, their behavior peculiarities in magnetic fields are revealed. Creating an integrated model helps predict the behavior of system and optimize the devices to achieve high technical performance.

P-45 Simulation of a Real Distribution Grid with Superconducting Fault Current Limiter

André Tiago Queiroz[1], Marcio Zamboti Fortes[1], Alexander Polasek[2] and Guilherme Goncalves Sotelo[1]
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The growth of generating sources connected to the power system and closer to the consumers increased the short-circuit level, due to the low impedance between the fault and the source. In addition to this, several equipment in the distribution network were installed decades ago. Since then, fault current levels have increased in many cases, due to modifications in the grid, such as the above-mentioned connection of new generation sources. This means that the system may not be properly protected during a fault occurrence. One potential solution for this problem is the insertion of superconducting fault current limiters (SFCL) in the grid. The resistive SFCL is a mature technology, especially in medium voltage levels, and sooner it may be largely commercialized and inserted in distribution grids. A proper study of these devices concerning how they affect the grid dynamics is necessary to correctly dimensioning and positioning them. In this context, a distribution network using data obtained from a real system of an utility was modeled using the software Alternative Transient Program (ATP). The SFCL was also modeled in ATP and the electrothermal analogy was used to solve the coupling between electrical and thermal phenomena that describes its behavior during a fault occurrence. The simulation results of the distribution system show that the SFCL is able to reduce short-circuit currents to values below the interrupting capacity of existing circuit breakers, in the first half-cycle, which makes possible to evaluate its performance for real applications in the power systems and their future installation by the utilities.

P-51 Full Three Dimensional Transient Simulation of Superconducting Coated Conductors Using Efficient T-A Formulation

Huiming Zhang
China Electric Power Research Institute, China

This paper proposes a new three dimensional FEM model based on T-A formulation for electro-magneto-thermal transient simulation of superconducting coated conductors. Current sharing and thermal interaction between superconducting layer and normal conducting matrix is simulated by extending the newly developed T-A formulation [1] with modified E-J power law. The modified E-J power law assumes that superconductor runs in parallel with the normal conducting matrix [2]. To calculate the fraction of the total current in the element that runs in the superconductor, an implicit equation is used to couple with the T-A formulation, which is performed within COMSOL environment. After the establishment of transient simulation model, quench propagation of superconducting coated conductors is modelled to compare the quench propagation and minimum quench energy with verified results. Finally, this fully electro-magneto-thermal simulation is compared with the electro-thermal modelled presented in [3] to investigate the influence of magnetic field interaction during the transient process. This model can be further applied in the dynamic simulation of fault current limiters during over current situation.

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P-53 Numerical analysis of AC loss in HTS coils wound with REBCO Roebel cables: effect of current distribution among strands on AC loss

Wenjuan Song[1], Zhenan Jiang[2], Mike Staines[2], Rodney Badcock[2] and Jin Fang[1]
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REBCO Roebel cable is a promising candidate for HTS power applications as it enables large current-carrying capability and has lower AC loss than equivalent non-transposed vertical stacks, especially in coil windings. 'Equivalent' stacks are side-by-side stacks with the same strand number, width, and spacing as the Roebel cable. The advantage of the continuously transposed Roebel cable is that current is equally distributed among the strands, minimizing the AC loss. In an HTS coil winding where each coil turn is composed of non-transposed side-by-side vertical stacks with the strands connected in parallel, current is distributed unequally among the strands because each conductor in the stack experiences a different magnetic field due to the difference in radial position. One previous report showed numerically that AC loss in coil windings can be reduced by utilizing Roebel cables due to their narrow strand width which is half of the width of conductors used for the coil windings [1]. However, there is no report on AC loss reduction effect in coil windings wound with Roebel cables due to equal current distribution among Roebel strands as compared to coil windings wound with non-transposed equivalent vertical stacks.
In this work we present numerical calculations for AC loss in 8/2 (eight 2 mm-wide strands) Roebel cable as a straight conductor and in four coil assemblies comprising one, two, four, and eight stacks of double pancakes (DPCs) wound with cable. The Roebel cable was modelled as two parallel stacks carrying identical current in each Roebel strand. Each DPC has 10 turns, and an inner diameter of 60 mm. 2D FEM analysis was carried out using the H – formulation implemented through COMSOL Multiphysics 5.3a.
Simulated transport AC loss results in the straight 8/2 Roebel cable were compared with previously measured results [2] as well as two parallel vertical stacks which have the same geometrical dimensions as the Roebel cable and an equivalent four-conductor vertical stack comprising four 4 mm-wide conductors. The stacks are modelled in parallel connection, with the same electric field applied to all strands, so that current is distributed between the conductors. The numerical AC loss results in the four coil assemblies wound with the 8/2 Roebel cables were compared with the results in coil assemblies wound with two parallel stacks which have the same geometrical dimension as the Roebel cable, and those in coil assemblies wound with the 4 mm-wide four-conductor vertical stack with unequal current distributions between conductors. No transposition is introduced at the connection between double pancakes, so the results are also representative of layer windings. The results are discussed in terms of the current distribution in the conductors and magnetic field distributions around the cables and coil assemblies.

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P-59 Numerical modelling of HTS tapes and HTS coils operating in PM linear motor

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Recent development of transportation systems, particularly in highly urbanized areas, is focused on personal rapid transportation (PRT) systems. Levitation systems and drive systems of PRT can employ superconducting parts. It is very advantageous mainly because of compact structure and high energy density. Drive systems of PRT is usually based on linear DC motor. Superconducting tapes are good candidates for DC motor coils. They needs detailed investigation on critical properties, particularly dependence of critical parameters on external magnetic field. In the DC motor magnetic field is constant but it varies during coils displacement and distance between coils and magnets.
The paper is focused on analysis of properties of HTS tapes, coils and whole driving systems based on linear DC motor with permanent magnets or bulk superconductors. The analysis based on FEM and Ansys Maxwell software is focused on properties of a single HTS tape operating in the presence of magnetic field generated by permanent magnets arranged in Hallbach array, properties of coils made of HTS tape in the same working conditions (as a coil of PM linear motor) and analysis of the magnetic field and forces generated by all superconducting linear motor (made of HTS coil and bulk superconductors). The analysis will include two different arrangement of permanent magnets (external field). An optimal arrangement between coils and magnets will be determined. In addition, an investigation concerning technological aspects of preparation of prototype (including cooling system, supplying system, control) will be carried out.

P-60 Superconducting Undulators for hard X-ray Free-electron lasers

Marco Calvi, Ciro Calzolaio, Giuseppe Montenero, Stéphane Sanfilippo and Thomas Schmidt
Paul Scherrer Institute, PS, Switzerland

The next hard X-ray line at SwissFEL, Porthos, will extend the photon energy of Aramis, coming to wavelength down to 0.03 nm. To reach this goal, harmonic lasing and inter-undulator chicanes will be used. The undulator period length has however to decrease to 10 mm while the K value has to increase to 2.4 with a vacuum gap above 4 mm. To achieve these parameters, superconductors are an enabling technology. In this work we provide at first an overview of HTS superconductors and then we present a detailed FEM magnetic model which is compared with the previous developed analytical models from the literature. An outlook for further experimental characterization of the superconducting materials is finally addressed.

P-62 Modeling high temperature superconducting magnetics with an open source finite element library

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The challenge of modeling the behavior of magnets composed of super conducting high temperature super conducting (HTS) tape such as no-insulation (NI) (RE)Ba2Cu3Ox (REBCO) pancake coils stems from the disparate dimensions of the tape (order 4 mm x 0.05 mm) and the coil (10's cm). Here, we present initial studies of the magnetic diffusion equation implemented with the scalable finite element framework, MFEM [mfem.org]. FEM allows us to simulate a quench process in a HTS magnets without recourse to equivalent circuit network models. In particular, our goal is to analyze the quench process in a large complicated HTS magnet system such as a tokamak magnetic fusion device. A MFEM simulation model to solve the magnetic diffusion and heat diffusion equations are built using the Petra-M framework that has been used previous for modeling of radio frequency heating in fusion plasmas [Shiraiwa et al, Nucl. Fusion 57 (2017)]. The model scales up to several 10s of millions of degrees of freedom (DoF) permitting the simultaneous resolution of both eddy currents and large scale magnetic fields. We will demonstrate initial verification studies, scaling behavior, and methodology used to model a simple double pancake coil composed of REBCO from charging to quench.

P-63 Power-Hardware-in-the-Loop operation of a purpose-built air-coil Superconducting Fault Current Limiter

Joern Geisbuesch, Felix Kaiser, Wescley T. B. de Sousa and Mathias Noe
Karlsruhe Institute of Technology, Germany

In this contribution the lay-outing and realization of an inductive Superconducting Fault Current Limiter (SFCL) hardware, which employs an air-coil design, and its closed-loop operation in a Power-Hardware-in-the-Loop (PHIL) environment are described. The SFCL device has been purposely built to be operated in the PHIL Training Station of the Institute for Technical Physics at the Karlsruhe Institute of Technology. At first the design choices are explained and detailed characteristics are discussed. For approval of the SFCL design and its function the device has also been modelled in COMSOL. Further the functioning of a general PHIL environment as a testing facility for devices based on new technologies and the particular set-up of the SFCL device in a closed-loop PHIL experiment are explained. Finally, measurements and results of the behavior of the air-coil SFCL are presented and compared with findings of a simulation that includes sophisticated modelling of the heat exchange. The SFCL simulation is implemented in the real-time environment of the PHIL station.

P-73 Modelling of Electromagnetic and Thermo-Fluid Dynamics Ocurring in ZFC-YBCO bulks under Alternate Magnetic Fields and Immersed in Liquid Nitrogen (LN2)

António José Arsénio Dos Santos Costa, João Filipe Pereira Fernandes and Paulo José Da Costa Branco
IDMEC / IST, Portugal

The scope of the work is to properly model the thermo-fluid processes in liquid nitrogen (LN2) during the yttrium barium copper oxide (YBCO) zero-field cooling (ZFC) and the YBCO heating in operation when submitted to alternate magnetic fields. The model is built in 2D and 3D finite elements (FE) tools, whose precision is verified by experimental validation. The objective is to precisely estimate the LN2 rate losses and temperature distribution evolution by FE simulation.

The LN2 temperature distribution evolution depends on the heat conduction and convection but also on the flow of N2 gas bubbles. During the initial ZFC of YBCO bulks, a significant LN2 rate loss is verified by phase change with formation of big size gas bubbles due to the high temperature gradients verified on the boundaries between the YBCO and LN2 domains [1]. In operation, the heating due to Joule losses from currents appearing by electromagnetic induction [2,3] may cause LN2 phase change when YBCO boundary

reaches temperatures higher than the LN2 boiling temperature. The LN2 temperature could also increase by influence of room temperature when no perfect thermal insulation is guaranteed [1].
Accuracy of the model used for the initial ZFC stage is shown by comparing the required time to cool the YBCO bulk, from environmental temperature down to the critical temperature of superconductivity and the associated LN2 mass loss during this stage. Appropriate modelling of room temperature influence is also validated by measuring the LN2 mass loss with the ZFC YBCO bulk without any applied magnetic field. The YBCO temperature increases also when in operation due to the Joule losses from currents appearing by electromagnetic induction. Another objective is to experimentally confirm the obtained LN2 average temperature increase evolution nearby the boundary of YBCO in operation.

This work is supported by FCT funds to IDMEC under LAETA Projects UID/EMS/50022/2013 and PTDC/EEEI-EEL/4693/2014 – HTSISTELEC and to the fellowship SFRH/BD/117921/2016 granted by A. J. Arsénio Costa as a PhD student.
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P-76 Magnetization of superconducting tube computed in 3D geometry using A-formulation in Comsol Multiphysics

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Our actual arrangement of superconducting tubular part of the magnetic cloak consist of several layers of CC tapes helically wound on a cylindrical former. It shows good shielding properties and low dissipation, and is easily scalable to bigger dimensions. In the first estimation of its electromagnetic behavior we have considered it as a hollow cylinder from superconductor characterized by its critical current density. The simulations were performed in 2D approximation neglecting the existence of end effects, and this hindered a direct comparison with experiment. When facing the problem in realistic 3D geometry, we first reverted to the commonly used H-formulation. However even with very coarse meshing the computation time was unacceptable when using the standard Comsol Multiphysics code. Taking into account our previous favorable experience with the A-formulation we decided to develop its application in 3D geometry. We show the results of 3D computations of magnetic field and current distribution for a hollow cylinder with the length comparable to its diameter. The validity of results is confirmed by comparing the calculated magnetization loops with experiments performed with a tube from HTS material.

P-77 Toward Improvement of First Brazilian HTS Power Cable – Faster 2D Simulation of a Current Distribution in 2G tapes for New Design

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Recently we finish the first phase of the first Brazilian project of a high temperature superconducting (HTS) power cable, the SUPERCABLE project. The project was created and executed in the Laboratory of Materials and Devices with Superconductors (LMDS) of the Physics Department of the Federal Rural University of Rio de Janeiro (UFRRJ) and it was sponsored by four major power utilities in Brazil: Companhia Energética de Minas Gerais (CEMIG), Transmissora Aliança de Energia Elétrica S.A. (TAESA), Transmissoras Brasileiras de Energia (TBE) and Companhia de Transmissão Energia Elétrica Paulista (CTEEP). The SUPERCABO Project was part of the “Programa P&D ANEEL” and a National Strategic Project.
As a first result of the project, a new facility of the LMDS has been built up in the UFRRJ, which allows for the activities of design, modelling, simulation, construction and testing HTS power cables. In this phase of the project we also designed a rigid HTS power cable with cold dielectric, 10 meters long, tri-axial, three phases, one with its own cryostat, to operate in a high voltage and high AC conditions.
One relevant and challenge activity is the numerical calculations involved. For such, finite element methods (FEM) were employed through the use of COMSOL MULTIPHYSICS, a commercial FEM based tool available. Although this is a very helpful tool, the concerned simulations are very much time consuming.
In this work we try to introduce some computation simplifications based on translation and rotation symmetry of the helix-shaped stranding of the cable with the aim to reduce the FEM computation to only one of the tapes considering the appropriate boundary conditions which include the influence of the remaining tapes.

For beginning, we consider the case where all tapes have the same current distribution. Although this is an approximation to the real problem, in which we neglect the possibility of a dispersion of the electrical current in the several tapes configuring the strand, it constitutes an interesting simplification of the problem that could help in the cable design.