Doctoral Theses in the Field of Large Scale Superconductivity in Finland

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Abstract **- Electromagnetics at Tampere University of Technology hosts the only group in Finland doing research in the field of large scale superconducting applications. Over the past 20 years the emphasis of the Group of Superconducting Power Applications has included projects on superconducting magnetic energy storage, HTS motor, deflection magnet, superconducting cable, separator and induction heater. Research has been conducted also on AC losses in HTS conductors and stability of LTS, HTS and MgB_2 conductors and coils. In total, these studies culminated in ten Ph.D. theses, out of which five only recently. Here, we review these five Ph.D. theses, and shortly introduce other Finnish superconductivity-related activity. An appendix characterizes briefly the doctoral study system in Finland.**

Keywords - Environmental impacts of superconductivity, magnetometer, electromagnetic design of power cables, stability of MgB_2, modelling of stress and strain

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I. INTRODUCTION

Superconductivity research at Tampere University of Technology (TUT) was initiated at the beginning of 1980s. The first project started in 1984. It was a feasibility study of superconducting magnetic energy storage for network stabilization. Work has been conducted within the Group of Superconducting Power Applications, first at the Laboratory of Electromagnetics, then at the Institute of Electromagnetics. The current name of this TUT unit is simply Electromagnetics. Over the past 20+ years, the Group

participated in 16 national and international research programs, coordinated some of these, organised MT-14 conference and published 10 doctoral theses (dissertations). Only recently, several projects ended resulting in five Ph.D. theses. In the Appendix, the doctoral study system at Finnish universities is characterized.

In addition to the research into large scale applications at TUT, other research activities in the field of superconductivity also exist in Finland. Basic physics and manufacturing of HTS thin films are studied at the University of Turku. Properties of helium and nuclear properties of solids are studied at very low temperatures at the Low Temperature Laboratory of Helsinki University of Technology (HUT). Also development work on SQUIDs has been carried out there in the past. Superconducting electronics is the main topic of VTT Technical Research Centre of Finland. Both HUT and VTT are located at the Otaniemi High-technology Park.

We also mention three industrial activities: (1) NbTi and Nb_3Sn conductors are manufactured by Luvata Oy at Pori, (2) SQUID sensors and readout electronics are fabricated by Aivon Oy at Otaniemi, (3) SQUID-based biomagnetometer systems, especially for brain research and diagnostics, are developed and fabricated by Elekta Neuromag Oy, in Helsinki. Web page addresses of all the institutions and companies mentioned above can be found in the European Guide.

One of the newest actors on the superconductivity scene is the Magnet Technology Centre at Pori, established in 2004. Their activities in superconductor and permanent magnet technologies include industrial research and research services, the organisation of seminars (such as European Summer School on Superconductivity 2008), management of national research programmes and promotion of technology transfer between universities and industry.

In this article we review our recent doctoral theses to give an overview of our past research activities at TUT. The titles, publication dates and authors are presented in Table I alongside their authors' contact information. At the end of this paper citations to the key publications of each thesis are given.

The first thesis to be presented in this review, *Environmental Impacts of Superconducting Power Applications* summarises the benefits of the superconductor usage in the electric power sector. The next thesis, *Hall Magnetometer for AC Characterization and Test Results of Bi-2223 Tape Specimens*, considers characterisation of high temperature superconductors (HTS) with a Hall magnetometer. After this a climax of our long lasting HTS research occurred when the thesis *Electromagnetic Design of Superconducting Coated Conductor Power Cables* was published in 2008. The stability of recently (2001) discovered superconducting material, MgB_2, and its use in power applications, such as superconducting induction heater, was considered in the next thesis, *An Electrical Engineering Approach to the Stability of MgB_2 Superconductor*. The latest thesis thus far, *Modelling Stress And Strain in Filamentary Superconductors with Finite Element Method,* is a mathematical survey to mechanical behaviour of superconducting composite conductors.

Next we will shortly describe the background of each thesis and also review their content. References used in this text are listed first, followed by publications generated by each dissertation. The authors will happily answer queries concerning their special know-how.

Table I. Recent theses at Tampere University of Technology considering applied superconductivity

Author	Defense	Title
Teemu Hartikainen contact: teemu.hartikainen@galilei.fi	2005-12-02	Environmental Impacts of Superconducting Power Applications
Mika Masti contact: mika.masti@fi.abb.com	2006-02-17	Hall Magnetometer for AC Characterization and Test Results of Bi-2223 Tape Specimens
Lauri Rostila contact: lauri.rostila@iki.fi	2008-05-09	Electromagnetic Design of Superconducting Coated Conductor Power Cables
Antti Stenvall contact: antti.stenvall@tut.fi	2008-08-08	An Electrical Engineer Approach to the Stability of MgB_2 Superconductor
Maria Ahoranta contact: maria.ahoranta@tut.fi	2008-10-24	Modelling Stress and Strain in Filamentary Superconductors with Finite Element Method

II. ENVIRONMENTAL IMPACTS OF SUPERCONDUCTING POWER APPLICATIONS

Publications: [5]-[10]

Superconducting power applications possess properties that can prove them environmentally advantageous over conventional electric power applications. Such are, for example, up to 50% lower losses, which means savings in electricity and thus savings in greenhouse gas (GHG) emissions from electricity production, and lesser demand for raw materials required to construct devices resulting in lower environmental impact of manufacturing.

This thesis reviews the superconducting power applications, namely generators, transformers, electric motors, cables, superconducting magnetic energy storages (SMES), and fault current limiters (FCL) by introducing first their theoretical background and then each application from the point of view of advantages they might offer. By starting from the mining of materials, a life cycle assessment (LCA) was conducted for commercial NbTi superconductor. Comparison between conventional copper wire and NbTi/Cu wire was made and magnets made of both materials were also examined from LCA-perspective. Detailed calculation of GHG emissions reduction potential of Finnish and European electrical networks was presented in view of the Kyoto Protocol, which requires the EU countries to reduce their GHG emissions by 8% from 1990 levels. This reduction should occur between 2008 and 2012.

Distributed generation (DG) networks have been proposed as one solution to introduce new renewable energy sources to the network and lower the environmental impact of energy production. Here, this issue was studied by examining the environmental advantages that superconducting devices could bring to a DG-network. It turns out in DG-networks the advantages of superconductivity are quite modest. The only

superconducting device having some energy-saving potential would be the flywheel energy storage with superconducting bearings.

Finally, magnetic separation as a way to reduce heavy metal emissions from steel mill wastewaters was studied. A prototype of an open-gradient magnetic separator was designed, constructed and tested. Further analysis showed that above certain break-even power, superconducting machinery can save electrical energy and thus emissions from electricity generation. When considering the complete life-cycle of electrical machines, superconducting devices become even more preferable from environmental point of view. With magnetic separators it is possible to efficiently separate heavy metals from fluid streams.

III. HALL MAGNETOMETER FOR AC CHARACTERIZATION AND TEST RESULTS OF BI-2223 TAPE SPECIMENS

Publications: [11]-[17]

The economically viable use of HTS superconductors in AC applications poses strict demands on the manufacturing costs and operational losses of superconducting tapes. Both these are minimised with an appropriate choice of tape cross-section and manufacturing process. They can be optimised by systematic testing of different combinations, but such testing is expensive, consumes plenty of time and provides only few answers as to the sources of the internal losses in the tested tapes.

In this thesis, a Hall-sensor-equipped moving magnetometer for AC characterisation was constructed to enable magnetic flux density mapping and to gain information about sample homogeneity and current penetration into multifilamentary Bi-2223 tapes. The work involved analysis of the reproducibility and accuracy of the measurement and calculation methods. In addition, DC measurements and their analysis were included to help visualise the differences between DC and AC maps. New numerical tools based on the discrete Fourier transformation were developed to determine the optimal current distribution among several assumed current penetration models.

The AC Hall magnetometer proved to be inexpensive, robust, simple to use, and well suited for tape manufacturers to test systematically their specimens. Numerical test tools for the estimation of the inversion errors proved to give tight error limits. Comparison between Hall sensor and magnetic knife measurements showed that these methods should be used complementary to examine possible current variations in the cross-section of the tape. An analysis based on Discrete Fourier Transform (DFT) was applied to the magnetic flux density maps measured on the tape surface – to estimate current penetration in superconducting filaments. With the help of this analysis it was possible to distinguish two-dimensional penetration into the tape cross-section.

IV. ELECTROMAGNETIC DESIGN OF SUPERCONDUCTING COATED CONDUCTORS POWER CABLES

Publications: [18]-[25]

Superconducting YBCO cables are the latest step in the development of HTS conductors. Their viability is constantly improving, because YBCO tapes are going down in price. The aim of the European Project Super3C is to design, manufacture, and test a superconducting 30 m, 1 kA, 10 kV forced liquid nitrogen flow cooled YBCO power transmission cable prototype. A successful design of this cable must combine cryogenic, mechanical, and electromagnetic aspects. This thesis focuses on the electromagnetic part, which aims at low AC losses, a high critical current with a small amount of superconducting tape, and good tolerance of fault currents. With this in mind, computational tools were developed to predict the above cable characteristics in self-field. The considered special characteristics of YBCO were highly nonlinear resistivity, *i.e.*, the high *n*-value, and high magnetic-flux-density-dependent critical current density. Another aspect addressed in modelling is the troublesome high aspect ratio (superconductor layer width divided by its thickness) of the YBCO.

A circuit-analysis-based model was developed to predict AC losses in YBCO cables. Predicted losses were close to those measured for a one-conductor-layer, 0.5 m YBCO cable. Due to the short distance between the terminations, the current did not distribute equally between different tapes in the cable. Rather, currents measured in individual tapes were different. However, computations suggested that the problem should disappear in a 30-m cable. In addition, an algorithm was developed to compute the cable's critical current to further improve the AC loss model. Results suggest that striation of the tapes and cable twist pitch can greatly affect the cable critical current. Also, tape critical current in the cable can be higher than in the self-field. The effect of cable fault current on current redistribution and temperature rise was analysed by solving the heat conduction equation together with Maxwell's equations. It was concluded that this cable, operating at 77 K, could cope with 0.5 s of sinusoidal 50 Hz 40 kA fault current without exceeding 89 K. However, this cable was not designed for fault current limiter use and its current limiting properties were not studied.

V. AN ELECTRICAL ENGINEERING APPROACH TO THE STABILITY OF MGB_2 SUPERCONDUCTOR

Publications: [26]-[36]

The high critical temperature, 39 K, and usable critical current characteristics of MgB_2 make it a highly interesting superconductor for practical applications. Unlike conventional low temperature superconductors, it can be used around 20 K where cooling is relatively easy with a cryocooler. In addition, long-length MgB_2 conductors can be manufactured of inexpensive raw materials with standard techniques. Although superconductivity in MgB_2 was discovered only in 2001, industrially manufactured conductors are already now available and several promising demonstration projects are underway. To develop a new application using MgB_2, detailed design methods are

required. Many modelling tools, but not all, can be adopted from approaches developed for conventional superconductors.

This thesis begins by introducing readers to the mathematical formulation of phenomenological models of electromagnetism, thermodynamics and engineering superconductivity. Upon this background, conductor characterisation in a conduction-cooled measurement station was studied, because short-sample characterisation forms the basis of magnet design. A model was proposed for computing the critical current of coils consisting of a conductor utilising a ferromagnetic matrix. Subsequently, the contribution of matrix permability to the average conductor permeability was determined and filament shielding by the matrix was considered when determining the coil critical current.

Based on the coil design, a stability margin must be determined for the coil. Thus, a numerical model was presented for computing the minimum propagation zone [1], a model that can be further used to determine the minimum quench energy and the normal zone propagation velocities. At the end of the thesis, the utilisation of MgB_2 in an EU-funded scientific industrial-scale induction heater project ALUHEAT [2] was considered. Currently Zenergy Power plc is promoting superconducting induction heater technology to commercial markets [3].

VI. MODELLING STRESS AND STRAIN IN FILAMENTARY SUPERCONDUCTORS WITH FINITE ELEMENT METHOD

Publications: [37] and [38]

Electrical properties of superconductors are very sensitive to mechanical loading. As the loading in practical applications is often very large, designers should know the mechanical behaviour of conductors well. With the finite element method (FEM), mechanical models involving complex loading situations and conductor geometries can be solved. Such models give local information on stress and strain states as needed, for example, for predicting a fracture. The aim of this work is to study mechanical modelling of Nb_3Sn and Bi-2223 filamentary superconductors with continuum models that are solved with FEM. The focus is on loading conditions that are typical in a magnet. Models are developed for thermal stress, bending, axial tension and transversal compression loading of a conductor.

Filamentary superconductors contain specific features that are either complicated to describe in a mechanical model or increase the need of computational resources in the FEM solution. In this work, an auxiliary model approach was proposed to model conductors with a large filament number and an on-off approach was suggested to describe creep deformation. In addition, the modelling of twisted conductor structures and electromagnetic forces was studied. Computational tests showed that the uncertainty of stiffness of Bi-2223 and in the material behaviour at high temperatures may cause significant error in results.

Results of the models were compared to available measurement data. The models agreed well with the measurements. Comparison of the FEM models to analytical models confirmed the benefits of the FEM models. FEM models allowed to model combined loading, like bending and axial tension simultaneously, and predicted a clear variation of stress and notable non-axial stresses that were absent in analytical models.

VII. CONCLUSIONS

This paper presents the recent Ph.D. theses at Tampere University of Technology addressing large-scale power applications of superconductivity. After publication, these theses have been made available online at the Database of Electronic Dissertations of Tampere University of Technology. [4] All of these except the last one, which is a monograph, are based on several publications and the thesis itself presents the background for the research and summary of the publications to the extent chosen by the author. General enquiries should be directed to Risto Mikkonen (risto.mikkonen@tut.fi).

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APPENDIX: DOCTORAL STUDIES IN FINLAND

A. Purpose

The purpose of postgraduate studies is to attain scientific knowledge and skill of greater depth than acquired for a master's degree, which can be applied in scientific research and the related practical work. The core of postgraduate studies is researcher education, ***i.e***., studies that prepare for research work and develop the ability to apply research results. High-quality research is an unconditional prerequisite for postgraduate and researcher education.

In studies for a doctorate in technology, students should familiarise themselves thoroughly with their field of research and demonstrate an ability to independently produce new scientific knowledge. The Doctor of Technology degree can be taken by a person who has a master's degree in a relevant field of technology.

B. The Scope of Studies

A doctoral degree comprises a thesis (a doctoral dissertation, Ph.D. thesis) and theoretical scientific studies.

The theoretical studies consist of a major subject (studies in the field of research) and studies that support the field of research. These include scientific general studies, a possible minor subject and other studies. Other studies comprise postgraduate-level studies that support the studies as a whole. The total normative scope of all these studies is 70 ECTS credits (cr). The scope of the major subject is a minimum of 40 cr and the scope of the minor subject a minimum of 20 cr. A minimum scope for the studies supporting major subject and general scientific studies has not been specified.

C. Doctoral Dissertation

A doctoral dissertation requires independent scientific work. With the dissertation, a student proves his or her ability to generate new scientific knowledge in the research field in question.

The dissertation can be a book written by the author alone (***i.e***., a monograph), it can consist of several scientific publications or manuscripts accepted for publication and their summary, or be a work that fulfils comparable scientific criteria. In a summary of several publications or manuscripts, the aims, methods and results of the research should be explained. Joint publications can also be included in the publications if the author has had an independent role in them. The dissertation is presented for public examination. When the dissertation consists of several publications or manuscript, a typical minimum requirement is from three to four to appear in scientific journals and two in conference proceedings. The publications and manuscripts are then collected as appendices of a book starting with the summary.

The thesis may be written in Finnish, Swedish, English or a language typical to the field of research.

D. Examination of a Doctoral Dissertation

The examination of a doctoral dissertation comprises three phases: the preliminary examination, public defence and evaluation.

1. Preliminary examination and permission to publish a doctoral dissertation

The faculty council appoints at least two preliminary examiners who are professors or hold doctoral degrees and are external to the university. The preliminary examiners provide a statement as to whether the manuscript is of sufficient scientific or artistic merit to grant permission for its publication as a doctoral dissertation. In their statement, the preliminary examiners assess whether the structure of the manuscript is consistent, the treatment of the subjects critical, the research based on the application of methods of scientific or artistic research, and whether the outcome achieved is sufficient in regard to novelty value and significance. Before writing the final statement, a preliminary examiner can demand changes in content or form and possibly further or control research.

2. Opponents and public defence of a doctoral dissertation

When the author of a doctoral dissertation has been granted permission to publish, the faculty council appoints one or two opponents using the same criteria as for pre-examiners. At a public examination of a doctoral dissertation, the opponents examine the dissertation by asking questions related to the dissertation from the doctoral candidate, which the candidate answers orally. An examination by one (two) opponent may take a maximum of four (six) hours.

3. Evaluation of a doctoral dissertation

Within two weeks of the public defence, the opponent, or when there are two opponents each of them - either together or separately, submits a written statement to the faculty office. A person present at the public defence may give notification of an intention to submit a comment. This comment should be presented in writing to the faculty office within two weeks of the defence. Based on the statements, the faculty council makes a decision in regard to approving the doctoral dissertation and the grade (excellent or approved).