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# A Course on Applied Superconductivity Shared by Four Departments

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In this paper, a course on applied superconductivity is described. The course structure is outlined and the learning objectives and the learning activities are described. The teaching was multidisciplinary given by four departments each contributing with their expertise. Being applied superconductivity, the focus was on an application, which could benefit from using superconductors. The application used in this course was superconducting generators for direct drive wind turbines. As part of the course, the students built a small-scale superconducting machine and set up FE (finite element) models of that machine as well as large-scale wind turbine generators with superconductors and PM (permanent magnet) generators, too. The course was assessed by a conference contribution and reports from the students. The quality of the course was evaluated by interviewing the students after the course had finished. The students were very pleased with the course and gave suggestions of how the course could be improved further.

*Keywords:* electrical machines, mathematical modeling, project-based learning, superconductivity, wind energy

## Introduction

The need for engineers that can CDIO (conceive, design, implement, and operate) in the interdisciplinary environments has been pushed by both industry and governments in recent years. This need is being answered in part by academia, by focusing more on interdisciplinarity in the learning process of engineering students (Richter & Paretti, 2009; Qualters, Sheahan, Mason, Navick, & Dixon, 2008), and by active learning initiatives, such as the CDIO initiative (Retrieved from http://www.cdio.org). It could be argued that interdisciplinarity in engineering is the obvious route to go, as most engineering problems in their very nature are interdisciplinary. Teaching interdisciplinary courses has, however, also received much attention outside of the engineering disciplines over the last of decades (Vars, 1987; Hall & Weaver, 2001; Sales et al., 2006; Kaprinis, Digelidis, & Papaioannou, 2009).

This paper presents an interdisciplinary course taught at the DTU (Technical University of Denmark) (Retrieved from http://www.dtu.dk/English.aspx) as an intensive three-week course in June 2010, as part of the Grøn Dyst (Green Match) initiative (Retrieved from http://www.groendyst.dtu.dk/English.aspx). The course was shared between four departments, namely, the Department of Electrical Engineering, Mathematics, Physics, and the Materials Research Division at Risø DTU. The course was on applied superconductivity and focused on superconducting electrical generators for wind turbine applications.

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## Superconductivity

Superconductivity is an area of physics that requires a thorough understanding of thermodynamics, electromagnetism, material science, and quantum physics (Schneider & Singer, 2000). Applied superconductivity focuses more on the component that superconductivity is applied to, e.g., electrical machines (Nerowski, Frauenhofer, Ries, Nick, & Neumüller, 2004), MRI scanners (Lvovsky & Jarvis, 2005), fault current limiters (Salasso, Imece, Delmerico, & Wyatt, 1995), electrical power cables (Noji, 1997), and therefore, does not necessarily require the same thorough foundation in theoretical physics.

In applied superconductivity, it is more important to understand the macroscopic characteristics and the constraints of the superconductors, rather than the details of the interaction between the electron pairs making up the superconducting condensate inside the materials. Superconductors have the unique ability to exhibit practically zero resistance under certain operating conditions. These conditions can be divided into three: Firstly, T (the temperature) has to stay below $T_c$ (the critical temperature); Secondly, B (the flux density) must be below $B_c$ (the critical flux density); and finally, the current density in the superconductor must stay below $J_c$ (the critical current density) (see Figure 1). The critical current density is dictated by the ability of a superconducting material to prevent the movement of circulating super current flow patterns called flux lines, which is created by a magnetic field applied to a superconductor. Thus, the critical current density is a function of both temperature and applied field $J_c(B, T)$. The flux lines inside the superconductor will gradually start to move as the critical surface in Figure 1 is approached and local heating will result in causing a fast suppression of the superconducting state. One of the challenges of building a superconducting machine is to ensure that the critical surface of the conductor is not exceeded in any part of the field winding coils.

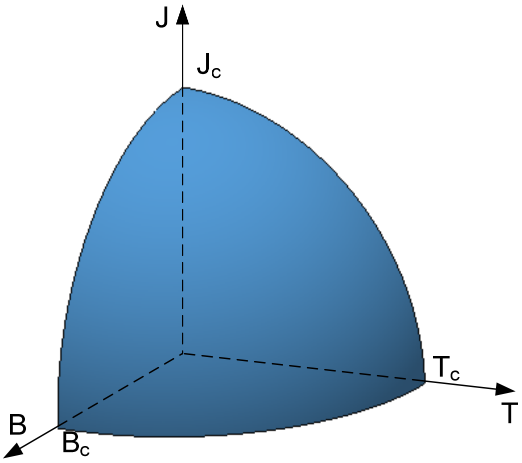

*Figure 1*. Surface of $T_c$ (the critical temperature), $J_c$ (the critical current density), and $B_c$ (the critical flux density).

As superconductors exhibit practically zero resistance under the right conditions, these are ideal for applications where large electric currents are advantageous. One such application, where superconductors could become commercially viable in the future is HTS (high temperature superconducting) wind turbine generators, where the HTS is used to establish the main magnetic field from the rotor. Such applications have been proposed by industry (Abrahamsen et al., 2010) as well as academia (Lewis & Muller, 2007), where the argument is that if a higher magnetic air gap flux density can be achieved by employing HTS, a smaller machine that delivers the same power may be constructed. The argument is based on the knowledge that the power produced by an electrical machine is the product of the rotational speed of the machine and the torque. The latter of which is proportional to the electric loading (the amount of current in the stator per meter circumference), the air gap flux density and the size of the machine. Therefore, if the air gap flux density can be doubled, then the size of the machine can be halved.

## Course Structure

The course was given as an intensive three-week course, where the students only focused on this particular course. The course was shared by four departments: the Department of Electrical Engineering, Mathematics, Physics, and the Materials Research Division, all with their own area of expertise. The course attracted nine students, all of which, except for one, had a thorough understanding of electrical machines before starting the course. The students were from the 3rd and the 4th years, meaning that the some were final year bachelor students, whereas others were the first-year master students. All of the students had followed previous project-based courses.

The beginning of week one was dedicated to supplementing the student's knowledge of superconductivity, wind energy, mathematical modeling of superconductors, and FE (finite element) modeling of electrical machines. The rest of week one, week two, and the beginning of week three, was spent in groups, where one group modeled a PM (permanent magnet) wind turbine generator to use as a reference for the HTS wind turbine generator; one group designed and modeled a large-scale HTS wind turbine generator; and one group modeled and built a small-scale HTS machine demonstrator. The end of week three was spent preparing a poster presentation, a short report per group, and a video presentation of the built HTS machine demonstrator. The course assessment was passed or not, and was based on the output from the students, i.e., the reports, the prototype demonstrator, and the poster presentation at the Grøn Dyst student conference at DTU.

## Learning Objectives and Activities

The learning objectives in this interdisciplinary course can be divided into three levels, where each level and the associated activity are explained in what follows.

### Basic Knowledge and Background Understanding

The students were introduced through lectures to the theory behind superconductivity; the argument and push for offshore wind farms; and the mathematical modeling of superconductors. These three lectures were given in the beginning of the course and gave the students a chance of understanding the argument for offshore superconducting wind turbines. The basic argument is briefly summarized here. The trend in the wind energy sector is to place the wind turbines offshore. The reason for this is that planning permission for onshore wind turbines has become difficult to obtain in the areas where the electricity is consumed, and that the wind turbines are better utilized offshore where the average wind speeds are higher than onshore. Being offshore, the installation costs per unit are high and the wind turbines are difficult to access for maintenance. This calls for more reliable and larger wind turbines. However, as the wind turbine size increases, the weight increases and can become unmanageable during offshore installation. Because of this, the generator weight should be limited, which if the wind turbine rating is increased to 10 MW, it will be very difficult to achieve with conventional technologies. Because of this, superconducting wind turbines for offshore applications, where the air gap B can be increased and hence the size of the generator can be reduced, might become commercially viable in the coming decade. This initial stage of the course helped the students *conceive* (CDIO (C—conceive; D—designed; I—implemented; and O—operation)) the problem at hand.

**Hands-on Experience**

The students gained hands-on experience with FE modeling of electrical machines, where each group had to build their own working FE model of an electrical machine. The first group constructed a small-scale HTS machine prototype and therefore built an FE model of this machine, which was validated with experimental measurements of the constructed prototype. The second group built an FE model of a large-scale 10 MW HTS wind turbine generator. To make the FE simulations more realistic, the second group used input from the first group, who had an experimentally validated FE model of a small-scale HTS machine. The third group built an FE model of a 3.0 MW PM direct drive wind turbine, which should correspond to what is publicly known about a commercially available 3.0 MW direct drive PM wind turbine generator. Once, the 3.0 MW model had been completed, a scaled-up 10 MW version was designed, which was used as a comparison generator or a reference that the large-scale 10 MW HTS generator from the second group could be compared to. During this stage of the course, the students collaboratively *designed* a solution for the problem at hand (CDIO), and *implemented* that solution in the form of building FE models as well as constructing a small-scale prototype (CDIO). Once implemented the students tested the prototype to validate the small scale FE and examined the available power in the large scale FE models. This part of the course covered the *operation*, which is also one of the four cornerstones of CDIO (CDIO).

**Applied Generic Skills**

The generic skills of teamwork, negotiation, communication, and presentation where exercised throughout the course and the demonstration of these skills became part of the final assessment. The groups had to work as a team on the assignments and were free to choose the path they wanted to reach their goals. Such freedom in the learning process requires that the students work as a team, and use their negotiation and communication skills to present and argue their ideas. The students also had to write a report on their contribution and give a poster presentation and a video presentation of their work. The reports and the presentations were used to assess the course. The students were therefore not only assessed on the technical content of the course, but also on their applied generic skills.

The assessment was passed or not and all nine students passed the course. It could be argued that the students would have been more motivated to work hard, if they knew that a mark was waiting at the end of the course. However, the experience from this course was that the students worked hard throughout the three-week period and that they worked hard on the presentations. It was noticed that the students did not spend much time on the reports, which would only be read by the teachers and hence would not become available in the public domain.

**Presentation**

The course was part of the Grøn Dyst (Green Match) initiative (Retrieved from http://www.groendyst.dtu.dk/English.aspx) at the DTU, where 200 students competed in presenting the best sustainable solutions to the modern society. The Grøn Dyst ended with a conference contribution, where the students had a chance to present their project and ideas. Based on these conference contributions, a winner was chosen and an award was presented.

The conference contribution for the course described in this paper was split in two. A poster presentation where the students argued the potential of HTS direct drive offshore wind turbines and where all parts of their work was presented. Secondly, a video demonstration of the constructed HTS machine prototype was made, where the machine was tested and cool-down was demonstrated. The machine had to be cooled down to 77 K (the boiling point of liquid nitrogen at atmospheric pressures), which caused vigorous evaporation of the nitrogen and worked very well for a video demonstration.

The conference contribution was given in a large forum, where fellow students and local companies were invited. As a novelty, the Danish Minister of Energy and Climate visited all the presentations and handed out the prizes for the best projects.

## Constructing the HTS Machine Prototype

The HTS machine prototype was constructed such that the students could validate their FE model and such that they could get hands-on experience in applied superconductivity. The budget for constructing the prototype was very limited, which was a challenge, because HTS machines are notoriously expensive and have therefore not yet been launched as a commercial product. As the prototype was constructed as part of the three-week course, the time limitation was also very strict, resulting in a further challenge.

To simplify the construction, a standard two-pole induction motor stator that was fixed to a customized aluminum frame was used (see Figure 2). The rotor was custom made from soft magnetic steel and the HTS tape was wound around the centre piece of the rotor (see Figure 3).

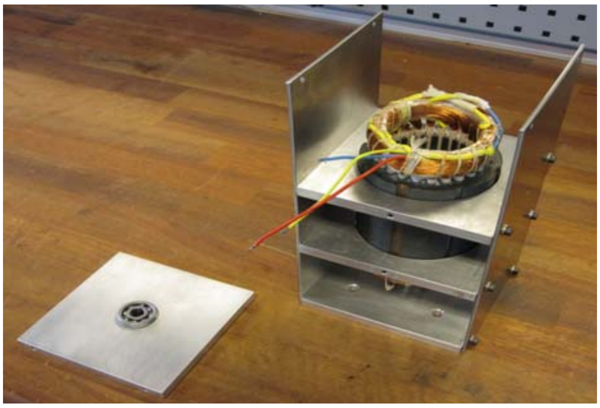

*Figure 2*. The two-pole induction motor stator mounted in a customised aluminium frame with a brass sliding bearing at the bottom and a ball bearing at the top.

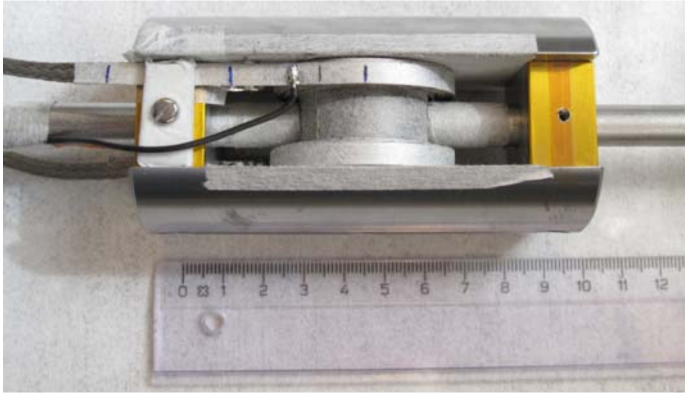

*Figure 3*. The two-pole custom made rotor with HTS tape (4 mm wide and 0.2 mm thick) wound around the rotor centre piece and a shaft to connect the rotor to the aluminium frame and the ambience.

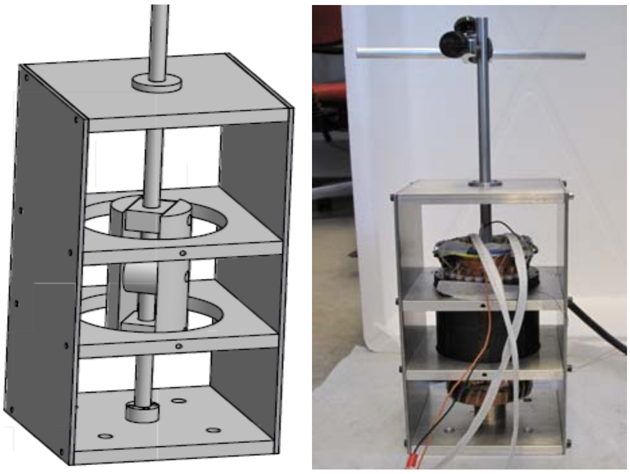

*Figure 4.* Simple HTS machine demonstrator, with a handle to demonstrate the torque as a function of angle. The figure on the left is a CAD drawing where the stator is excluded and the figure on the right shows the complete machine.

In an HTS machine, DC (direct current) is constantly supplied to the HTS tape. As the rotor, which contains the HTS tape, normally would spin, slip rings would be required, which was not feasible in this low-budget three-week course. Therefore, a static machine was constructed, where the torque and air gap flux density could be measured as a function of rotor angle. Figure 4 shows the machine setup with the handle that was used to demonstrate the torque as a function of angle.

The superconducting machines that have been constructed and proposed in the past usually have a cold region, where the superconductors reside and a warm region at ambient temperatures for the rest of the machine. The cold region would normally be thermally insulated by a cryostat and cooled down to 30–40 K by a cryocooler. Buying or constructing such components in this context would be completely unrealistic, as they would cost tens of thousands of dollars. A solution to this was to buy a flamingo box where the entire machine could be submerged into liquid nitrogen (see Figure 5). This machine, therefore, did not have two separate regions, but rather had the entire machine placed in a cold region.

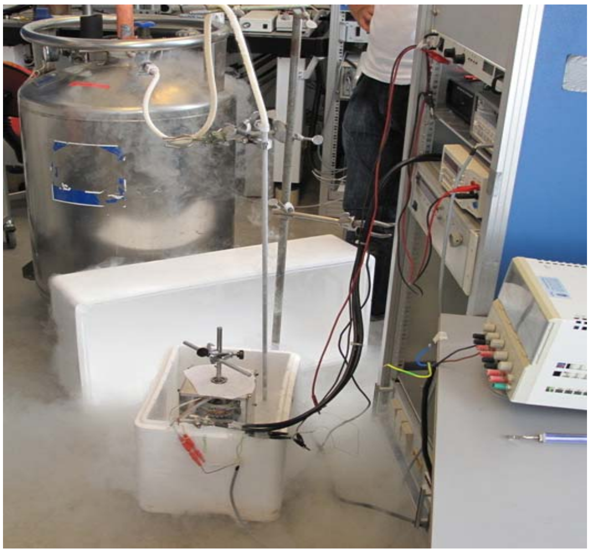

*Figure 5.* The HTS machine prototype setup after cool-down and during testing.

## Technical Results

The three groups of students all built FE models of electrical machines. As mentioned earlier, the first group built an FE model of the constructed small-scale HTS machine prototype; the second group built an FE model of a large-scale 10 MW HTS wind turbine generator; and the third group built an FE model of a 3.0 MW and a 10 MW PM wind turbine generator.

### The First Group

The first group could validate their model against experimental measurements. This model is seen in Figure 6, which shows the HTS machine prototype split in half axially due to symmetries. The model had to be 3D (three dimensional) because the flux has a natural 3D path in the rotor, where the flux will concentrate in the centre of the rotor and spread out in the pole pieces of the rotor. The first group could feed their validated information to the second group, who did not have a chance to validate their simulations experimentally, although their model could be validated against analytical calculations.

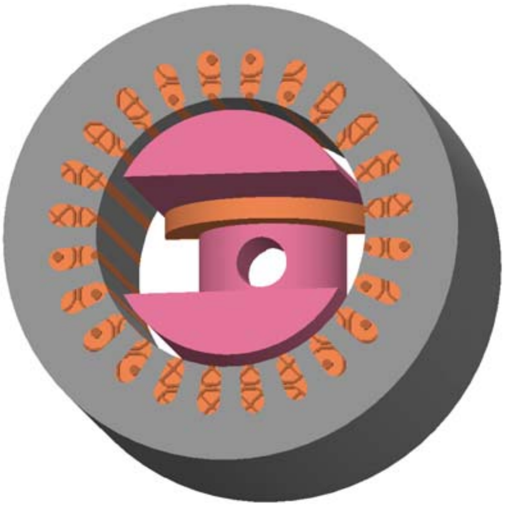

*Figure 6*. 3D FE model of the HTS machine prototype. Purple: soft iron of rotor; brown: HTS tape circular winding; gray: stator core; and brown with crosses and dots: stator copper windings.

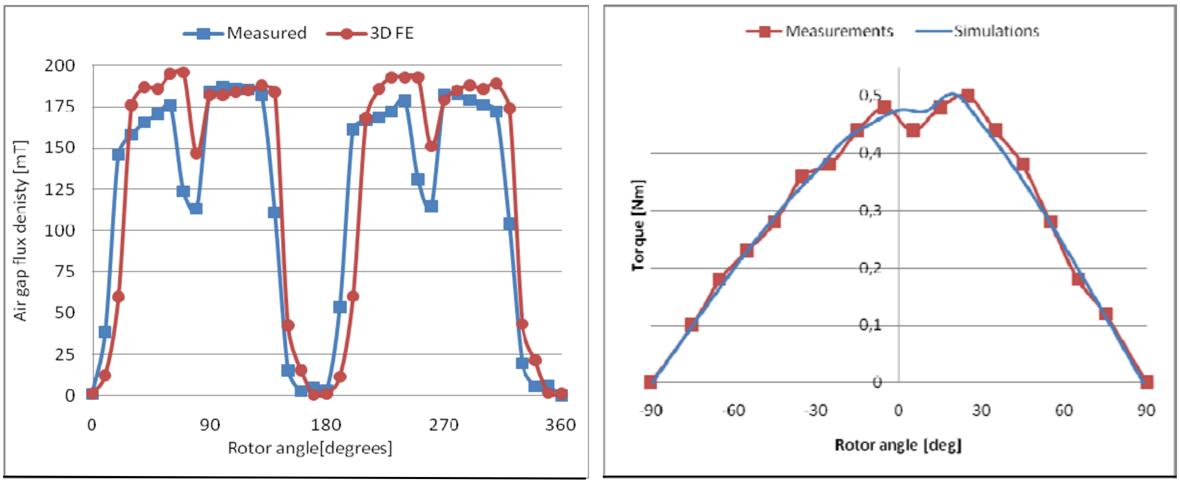

*Figure 7*. Experimental and simulation results for air gap flux density and torque as function of the angular displacement of the rotor with respect to the stator magnetic field at $T = 77$ K. A constant current of 50 A was applied to the rotor and peak stator current of 1.0 A was used in the torque experiment.

As the machine could not rotate due to the lack of slip rings, it was not possible to measure the induced voltage, power, or other quantities associated with rotating operation of the machine. It was, however, possible to measure the torque of the machine as a function of angle and the air gap flux density. The torque was measured by a simple Newton Meter attached to the handle. The air gap flux density was measured by inserting a hall probe in the air gap. The students also estimated the critical current from the FE model of the machine and ensured that the current supplied to the HTS coil was below the critical current, which would cause the superconductor to go into a non-superconducting state.

The measured torque and the torque from the FE simulations are found in Figure 7 on the left. The measured air gap flux density and the flux density from the FE simulations are found in Figure 7 on the right. The equipment used by the students to measure the air gap flux density and the torque, was not state-of-the-art equipment but rather simple low-budget solutions. The simulation results and the experimentally measured results are therefore considered a rather good match.

### The Second Group

The second group built an FE model of a large-scale 10 MW HTS wind turbine generator. The purpose of this model was to show that it could be technically feasible to design a 10 MW HTS generator that had a manageable size for wind turbine applications. The students did not design a "ready to build" generator, which would take many years to complete, but made a simple model that demonstrated the benefits of applying superconductors to electrical machines. To make the FE simulations more realistic, the second group could use input from the first group, who had an experimentally validated FE model of a small-scale HTS machine. The FE model from the second group is found in Figure 8 and the results for comparison with the PM generators from the third group are found in Table 1.

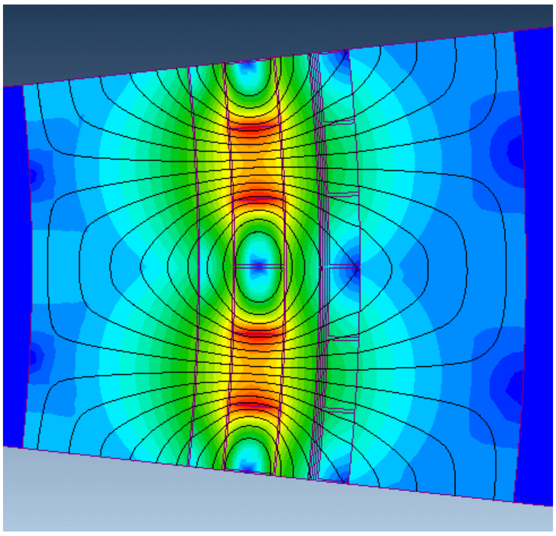

*Figure 8*. FE model of one pole pair of a 10 MW HTS wind turbine generator set up and analysed by the second group.

### The Third Group

The third group built an FE model of a 3.0 MW PM direct drive wind turbine, which should correspond to what is publicly known about a commercially available 3.0 MW direct drive PM wind turbine generator. Once, the 3.0 MW model had been completed, a scaled-up 10 MW version was designed, which was used as a comparison generator or a reference that the large-scale 10 MW HTS generator from the second group could be compared to. The FE model for the 10 MW PM generator from the third group is found in Figure 9 and the results for comparison are found in Table 1.

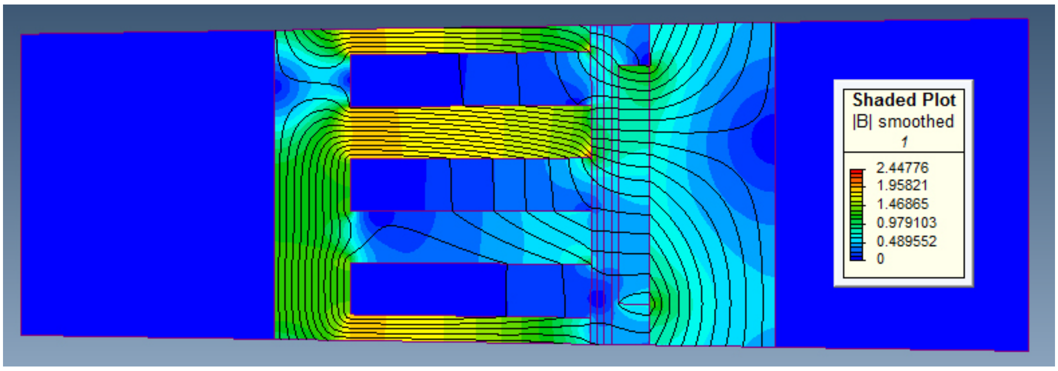

*Figure 9*. FE model of one pole pair of a 10 MW PM wind turbine generator set up and analysed by the third group.

The simulation results for the HTS wind turbine generator and the PM wind turbine generators are found in Table 1. Based on these simulation models, the argument for HTS wind turbine generators became very clear to the students. Looking at the size of the generators, it is clear that the 10 MW HTS generator designed by the students in the third group, has a similar size to the 3 MW PM generator designed by the students in the second group. Therefore, it became very clear to the students how superconductors could be applied in electrical machines to construct a small machine with a high power output. In this way, the students gained hands-on experience, through which they learned how superconductors can be used in a relevant practical application.

Table 1

*Comparison of the Students Results for the HTS and the PM Wind Turbine Generators*

| | 3 MW PM | 10 MW PM | 10 MW HTS |
|---|---|---|---|
| Power rating | 3 MW | 10 MW | 10 MW |
| Outer radius | 4.2 m | 8.8 m | 5.0 m |
| Length of generator | 1.4 m | 1.7 m | 1.2 m |
| Volume of generator | 19.4 $m^3$ | 103.4 $m^3$ | 23.6 $m^3$ |

The authors would like to emphasize that the technical specifications of the designed PM and HTS generators found in Table 1, should not be referenced as valid research, because the designs have been made by students in a three-week period and have not been validated or in any way optimized by any staff members.

## Student Survey

The quality of the course was surveyed by interviewing students after the course had been completed and after the assessment had been completed. An interview was chosen in favour of a written questionnaire as this could provoke a discussion, where other aspects could be brought forward that otherwise would be difficult to assess in a questionnaire. As the interview was conducted after the course and the assessment had been completed, the students felt safe to give their honest opinion on the course. It could still be argued that students would have difficulties expressing their honest opinion in an interview with the teacher. However, this was not noticed and would not be expected in Denmark, where a very relaxed student/teacher relationship is the norm. Denmark is also known for its flat-structured hierarchy, which also was one of the reasons for choosing this quality assessment scheme rather than a written questionnaire. The survey response can be divided into three categories: positive, negative, and suggestions.

**Positive**

The short heading "positive" covers the factors that motivated the students to work hard and take ownership of their own learning. These factors are summarized in bullet points:

(1) The three-week course was an elective course and therefore the students would only choose it if they were interested in the topic. This gave a good foundation for motivation;

(2) Most of the students (eight out of nine) had taken an introductory course on electrical machine design in the previous semester and saw this course as a chance to apply the theory that they had learned;

(3) One of the four departments that taught the course is a research institute (Risø) based on off-campus. The contributions from Risø were considered a novelty to students who would spend most of their time on campus;

(4) The interdisciplinary nature of the course exposed the students to a wider field of study, than a more traditional course would;

(5) The course was a three-week intensive course, where the students only focused on one course. This allowed the students to retain the focus on one topic for three weeks, rather than switching between courses as would be common in an academic term.

**Negative**

The short heading "negative" covers the factors that did not work so well during the course. Generally, the feedback was positive and the students were satisfied with the course. However, there were aspects that did not work as well as they could have. These factors are summarized in bullet points:

(1) It was felt that communication between the three groups did not work as well as it could. The group that constructed the small-scale HTS machine prototype took pictures during the construction period and shared this with the other groups. But it was felt that overall the communication between groups was lacking;

(2) The group backgrounds were too similar. Eight out of nine group members were electrical engineering students, who had studied introductory electrical machine design, whereas the 9th group member was a mechanical engineering student. It was felt that the group strengths were too homogeneous and that further benefits could have been gained if the group members had more diverse backgrounds;

(3) In the poster presentation, all of the material had to be presented on one poster, meaning that the work from three groups had to be presented on one poster. It was not felt that there was sufficient space to adequately present the students' work with only one poster.

**Suggestions**

The suggestions on how to improve the course in the future are summarized in bullet points:

(1) It was suggested that an online group would be formed, either as part of a social networking Website or as part of the university Website, where the individual groups could post daily updates on their progress. In this way, the group communication could be improved significantly. Such a group was available but the students were not sufficiently informed and therefore did not use it;

(2) It was acknowledged that learning should be the students' responsibility, but it was suggested that more guidance was provided in how the groups should organize themselves. The group organization when it

came to the final presentation and which contribution that would be made by each group did not work optimally. This could have been improved if the students were better informed early on in the course, about the presentation format and the amount of work that it would require to prepare the presentations;

(3) The students would have preferred to receive a mark in the assessment rather than a pass or not. The reason for this being that the students were motivated to work hard during this course and would, therefore, be more likely to receive a high mark, which would contribute towards a higher final average mark.

## Conclusion

This paper describes a multidisciplinary three-week course on applied superconductivity shared by four departments. Each department contributed with their expertise and aided in creating a multidisciplinary learning environment. The course was assessed by a report and a presentation, consisting of an oral part and a video demonstration part. The purpose of the course was to teach applied superconductivity in a relevant application that the students could identify with. Applied superconductivity is naturally a multidisciplinary topic, where physics, mathematics, and several engineering disciplines are involved. It was, therefore, natural that such a topic was taught as an interdisciplinary course.

The quality assessment of the course was carried out by interviewing the students after the course had been completed and after their assessment had been completed. The student assessment showed that the students were generally pleased with the course and the interdisciplinarity of the course. In addition, the students felt motivated partly because the course was an elective course, an intensive three-week course, an interdisciplinary course, and that there were off-campus activities. Most of the criticism from the students was based on the communication between groups and the group organization, when it came to the final presentations. The students therefore suggested for the future, that the teachers would spend some time on facilitating improved group communication.

If such a course was given in the future, then a more standardized form of project management and documentation could be implemented, such that it would be easier to offer the course to larger groups of students. This course was very special in that some of the students built an electrical machine prototype. Such prototypes would be relatively expensive if several were to be built, but the learning exercise of modeling a machine and validating the results experimentally is very valuable and might be considered more valuable than the construction of the machine. One way of opening-up for larger number of groups, would be by allowing the students to carry out experiments on the already constructed machine and use that data to validate their FE models of the machine.

Based on what has been reported, the authors feel that the course went well and that the course objectives were met through the different course activities.

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