HTS synchronous machine critical current modelling and comparison with tests

To cite this article: P G O’Brien and R R Taylor 2020 J. Phys.: Conf. Ser. 1559 012135

View the article online for updates and enhancements.

Abstract. 
Superconducting rotating machines generate high magnetic fields and for economic application of these machines and to ensure safe and reliable operation accurate assessment of the critical current of the superconductor is required. This paper describes a process to assess the critical current for a HTS synchronous machine with a superconducting rotor using a self-consistent numerical model. The model is used to study the critical current of first generation (1G) Bi-2223 pancake coils under self-field conditions for coil tests as well as within a machine magnetic field under full load conditions. Model results are compared against test measurements on individual HTS pancake coils as well as a double pancake coil in an operating synchronous machine at the Queensland University of Technology (QUT) test facility. Results obtain show that the self-consistent model is fast and accurate in determining the effective critical current of superconductors in such applications. Insights from the modelling assist with the design and optimisation process of the superconducting coils, selection of coil voltage sensing locations to detect the risk of quench and establish safe margins for the superconductor operating current.

1. Introduction 
There is active ongoing interest in high temperature superconducting (HTS) machines which offer unique technology advantages including improved efficiency, higher power density and high electrical stiffness in electric power systems [1]. Progressing HTS machine applications requires a high standard for performance and resilience and one of the most important factors in the design of the machines is the critical current, $I_c$, of the superconducting device.

Accurately estimating the effective $I_c$ for a device can be complex due to factors including different geometries of machine topologies, varying electromagnetic design conditions and the unique characteristics of a selected superconductor including temperature and angular magnetic field dependence. In large magnetic fields such as rotating machines it is possible to estimate the critical current using the load line method [2]. However, our motivation was to utilise a model where the critical current is estimated based on local magnetic flux density and orientation in the tape domain and the current density and flux density ($J - B$) dependence of the tapes. The $\mathbf{H}$-formulation has been used for estimation of the critical current of circular pancake [3] [4]. Solving a time-dependent transient model however requires a large computation time. A self-consistent model [5] for estimating steady state $I_c$ was recently proposed which is accurate and provides a fast computation time suitable for assessment of the effective $I_c$ of power devices.
In this work we have adopted the self-consistent model to evaluate the $I_c$ of the rotor HTS pancake coils in the Siemens HTS1 demonstrator located at the Queensland University of Technology (QUT) test facility. Original empirical design and test data has been used with modern numerical techniques to assess the effective $I_c$ of the HTS pancake coils under self-field conditions as well as within the machine magnetic field environment at full load conditions. Model results in each case are compared with test measurements.

This paper is organised as follows: in section 2 a description of the HTS1 demonstrator is provided as background including the machine rating, HTS rotor coils and Bi-2223 tape $I_c$ data used in the model. In section 3 we describe the theoretical model, we compute the effective $I_c$ for a single pancake coil in self-field, a double pancake coil in self-field and a double pancake coil in the machine with a magnetic environment under full load conditions. In each case we compare the results from the model with those obtained from test measurements. In the conclusions, we summarise the main findings of this work.

2. HTS1 machine and Bi-2223 rotor coil data

2.1. Key details of machine

The Queensland University of Technology (QUT) superconductivity laboratory test facility utilizes a superconducting machine demonstrator (HTS1) developed by Siemens [6]. The 400 kW 4 pole machine has a non-superconducting copper stator and a superconducting four pole salient pole rotor. Key details of the HTS-1 demonstrator are shown in Table 1.

| Description                | Value | Units |
|----------------------------|-------|-------|
| Nominal power output       | 400   | kW    |
| Rated line-to-line voltage | 400   | volt  |
| Rated stator current       | 577   | ampere|
| Rated frequency            | 50    | hertz |
| Number of poles            | 4     | -     |
| Rated DC excitation        | 48.95 | ampere|
| Rated speed                | 1500  | 1/minute|
| Air-gap peak magnetic flux density | 1.1 | T     |
| Rotor field coils          | Bi-2223 | -     |
| Rotor operating temperature| 27    | K     |

The HTS salient pole rotor is constructed from low-temperature magnetic iron with pancake coils of first generation (1G) Bismuth based Bi-2223 tape [7] stacked on the four rotor poles. The cold rotor components are contained within a warm rotating cryostat and outer concentric damper shield. The stator winding is a toothless, air-cored winding using copper Litz wire and fibreglass reinforced plastic (FRP) winding support supported within a cylindrical steel iron stator yoke.

2.2. Bi-2223 rotor pancake coils

About 9.5 km of Bi-2223 conductor is used for the 48 rotor pancake coils in the machine. The superconductor is Bi-2223 with magnesium (Mg)-reinforced silver (Ag) sheath manufactured by
Nordic Superconductor Technologies (NST) [8]. Dimensions for the bare NST Zerome Hercules conductor used in the HTS1 machine is approximately 3.13 mm x 0.21 mm.

HTS tape data at the time (circa 1999) was not well defined as conductors and measurements were on a very basic technology level. According to the original NST specification, the Bi-2223 tape critical current at 77 K, self-field (SF), scattered between 30 A to 47 ampere measured on the entire length of tape for each tape coil. Measured on random short samples by Siemens, the scatter was even worse between 19 A to 45 A at 77 K SF. Available tape performance data and characterisation of the Bi-2223 tape published at the time was given in a number of references [7], [9], [10].

2.3. Bi-2223 tape sample test
The critical current of HTS coils within a rotating machine requires knowledge of the superconductor performance with temperature and variation of the magnetic field magnitude $B$ and orientation $\theta$ to the tape surface. Critical current measurements on a representative Bi-2223 tape sample (circa 1999) was conducted by the Victoria University of Wellington, Robinson Research Institute, to gauge the critical current density temperature and field $J_c(B, \theta)$ dependent characteristics of the early tape for use in our model.

The critical current measured was $I_{c0} = 17.2$ A, $n=13$ at 77.5 K SF. The self-field temperature dependence of $I_c$ from the sample (normalised to the self-field critical current measured at 77.5 K) is shown in Figure 1. The temperature dependence of the self-field critical current was found to be linearly increasing with decreasing temperature. An increase in performance is noted at temperatures below 77 K. At 27 K (the nominal operating point of the HTS1 machine) the critical current is approximately 4.4 times $I_{c0}$ at 77.5 K SF.

![Figure 1. Typical Bi-2223 sample normalised critical current versus temperature ($B = 0T$).](image)

The critical current $I_c(B, \theta)$ characteristics for the sample is highly anisotropic. The field angular $I_c$ data measured at 27 K in field magnitudes from 0.5 T to 3.0 T is shown in Figure 2. The angle dependent data clearly shows asymmetry, that is the peak $I_c$ is not at 90 degrees. Also the peak is lopsided with the slope (or downturn) of the $I_c$ curve for field angles greater than 90 degrees being steeper than for field angles less than 90 degrees.

3. Computation of the $I_c$ of the machine HTS rotor coils
3.1. Self-consistent critical current model
A self-consistent critical current model has been adopted based on a steady state current density $J$ near $I_c$ [5]. The model assumes the magnetic field inside the superconducting regions has relaxed and the current density $J$ has reached a dc steady state and there is a uniform flux flow over the length of a conductor. The model equations are given as follows:

$$E = E_c \frac{J}{J_c(B)} \left| \frac{J}{J_c(B)} \right|^{n-1}$$

(1)
The $E - J$ power law relationship \cite{11} in equation (1) describes the electric field $E$ at which the current density $J$ reaches a critical value $J_c(B)$ at the electric field criterion $E_c$ (1 \text{ \textmu} \text{V cm}^{-1} adopted in our case). Introduction of the auxiliary variable $P$ simplifies the problem by avoiding directly solving the non-linear $E - J$ power law relationship \cite{5}.

In the model when the current in a conductor reaches a critical current $I_c$ (that is $J = J_c(B)$), then $P = 1$ and $E = E_c$. In the case of 2D coils comprising $m$ number of coil turns, one auxiliary variable $P_i$ is necessary for each conductor in the cross section, that is $P_i \mid i \in 1, 2, ..., m$. The variable $P_i$ is chosen to impose the same current $I_{\text{cond}}$ in each of the $m$ conductors by the following:

$$P_i = I_{\text{cond}} \int_{\Omega_i} P_i J_c(B) dx dy$$

By substituting equation (2) into (1) the voltage drop per unit length $E_i$ in the $i$th conductor can be obtained by the following:

$$E_i = E_c P_i |P_i|^{n-1}$$

The field problem formulation from Maxwell's equations can be described by the governing equations $\nabla \cdot B = 0$, $\nabla \times H = J$ and $B = \mu H$. The magnetic vector potential $A$ defined as $B = \nabla \times A$ is used in the field problem to solve for the current density and magnetic field in individual conductors. The model solves in 2D the equation for magnetic vector potential $A$ with $J = J_c(B)P$ in equation (6):

$$\nabla \times \frac{1}{\mu} \nabla \times A = J = J_c(B)P \frac{J}{J}$$

As noted by Zermeño et al \cite{5} the $P_i$ values indicate how close an individual conductor is to it's critical current. For a given electric field $E$ the model does not consider the dynamics of the voltage drop where the current density is far from the critical current value \cite{5}. Different critical current criteria can be used in the model to assess the effective critical current of a coil. In our case we have adopted two criteria:
• The critical current \( I_c \) at which the sum of the voltage drop per unit length \( E_i \) in each turn divided by the coil length has reached the critical electric field \( E_c \). This condition can be expressed as \( \sum_{i=1}^{m} E_i/l_i = E_c \) or using (5) as \( \sum_{i=1}^{m} P_i |P_i|^{n-1} l_i = L \) where \( l_i \) is the length of the \( i \)th turn and \( L \) is the total coil length. This is designated the SUM criteria.

• The critical current \( I_c \) at which the individual voltage drop per unit length \( E_i \) has reached the critical electric field \( E_c \) in at least one turn in the coil. This condition can expressed as \( \max_{i \in 1,2,...m} P_i = 1 \) or \( E_i = E_c \). This is designated the MAX criteria.

The SUM criteria models the critical current of the coil based on the coil’s end-to-end voltage satisfying the electric field \( E_c \) criteria (1 \( \mu \)V cm\(^{-1} \)). As a consequence of the self-field generated and the interaction of multiple turns of the coil the SUM criteria may mask over-critical current conductors in some parts of the coil. The MAX criteria can be adopted in the model to assess the maximum critical current the coil can carry without exceeding the critical electric field \( E_c \) in any turn of the coil.

3.2. Effective \( I_c \) of HTS coils under self-field

The self-consistent model was used to assess the \( I_c \) of an Bi-2223 tape coil under self-field conditions. In order to calculate the current and field distribution a 2D axisymmetric finite element (FE) model was used in the COMSOL AC/DC Module Magnetic Fields Interface. The 2D FE model uses the magnetic vector potential \( A \) and electric potential \( V \) as state variables with solving regions comprising superconducting regions and air regions [12].

The Bi-2223 tape was modelled as a homogenous domain by an ellipse with the approximate area of the superconducting multi-filamentary region [13]. As the area of the homogenised domain is larger than the real superconducting area the tape self-field critical current density \( J_{c0} \) is scaled as follows:

\[
J_{c0} = I_c / S_{eq} \tag{7}
\]

where \( S_{eq} \) is the area of the homogenous domain ellipse and \( I_c \) is the critical current for the tape. The scaling ensures the local magnetic field to the tape is accurately modelled [14].

The representative Bi-2223 tape was modelled with an angular dependence \( J_{c}(B, \theta) \) in elliptical form [15] as described in equation (8) below:

\[
J_{c}(B_{\parallel}, B_{\perp}) = \frac{J_{c0}}{\left[ 1 + \sqrt{(kB_{\parallel})^2 + (B_{\perp}/B_c)^2} \right]^b} \tag{8}
\]

with parameters \( J_{c0} = 2.4 \times 10^8 \text{A m}^{-2} \) \( (I_c = 41\text{A}) \), \( k = 0.1 \), \( B_c = 0.012\text{T} \), and \( b = 0.55 \), corresponding to a typical Bi-2223 tape at 77 K.

The model was evaluated on a single coil comprising 81 turns of Bi-2223 (nominally the HTS1 top coil on pole A) analysed under self-field at 77 K. Figure 3 shows a plot of the magnetic flux density in the coil under the SUM criteria.

A plot of the auxiliary variable \( P_i \) which indicates how close each tape in the turn is to the critical current is shown in Figure 4. The analysis shows that the inner turns experience the highest magnitude of magnetic field. However, the magnetic field angle is orientated closer to the parallel axis of the tape \( (a-b \text{ axis}) \) at the inner and outer turns of the coil, and orientated to the perpendicular axis of the tape \( (y \text{ axis}) \) through the centre region of the coil. Due to the highly anisotropic characteristic of the Bi-2223 tape, perpendicular field \( B_{\perp} \) is less favourable to the tape \( I_c \). As the \( P_i \) plot shows in Figure 4 the turns in the coil region centred around turn 30 determine the coil \( I_c \). The \( I_c \) value determined for the coil end-to-end voltage under original tests at 77 K was 22.8 A. The \( I_c \) of the single coil under self-field at 77 K calculated by the model is 21.9 A (an error of -3.8% with respect to the test data).
A second case of a double pancake coil comprising 81 turns and 118 turns of Bi-2223 on the top and bottom layer respectively of the coil (nominally the HTS1 top double pancake coil on pole A) was analysed under self-field at 77 K. Figure 5 shows the magnetic flux density plot in the coil again under the SUM criteria.

The $I_c$ value determined for the double coil end-to-end voltage under original tests at 77 K SF was 18.5 A. The $I_c$ of the double coil under self-field at 77 K calculated by the model is 19.0 A (an error of +2.7% with respect to the test data).

### 3.3. Effective $I_{coil}$ of the HTS rotor coils under machine field conditions

The self-consistent model was adopted to assess the coil critical current $I_{coil}$ under field conditions within the machine. A 2D finite element (FE) model of HTS1 in the A form was developed in
COMSOL Multiphysics [16] using the machine geometry and electromagnetic design parameters. The 2D FE analysis is completed using a radial cross-section through the machine in the the $x - y$ plane assuming the planar magnetic field is the same in each cross-section of the machine along its length in the $z$ axis [17]. Three dimensional (3D) effects (e.g. stator end winding and rotor field winding end turns) are not considered. The Bi-2223 tape was modelled with an angular dependence $B(\theta)$ from the Bi-2223 sample test data at 27 K scaled by a function [18] [19] as described in equation (9) below:

$$B(\theta) = \epsilon \theta B_{\theta} = B \sqrt{\cos^2 \theta + \sin^2 \theta / \gamma^2}$$

(9)

The normalised $I_c$ versus scaled field $B_{\theta}$ data with $\gamma = 8$ is shown in Figure 6. Due to the asymmetric and lop-sided peak of the field angular dependent data discussed in section 2.3 the normalised $I_c$ data points lie between upper and lower bound curves. An interpolation function was used with minimum normalised $I_c$ data to provide a conservative estimate of the effective $I_c$ for the machine.

![Figure 6. Scaling of angle-dependent $I_c$ data of the Bi-2223 sample with $\gamma = 8$ at 27 K.](image)

Three pancake HTS rotor double coils were each modelled including coil A2 comprising 240 and 259 turns, coil A4 comprising 216 and 187 turns and A6 comprising 118 and 81 turns (as per section 3.2) located in the stack on Pole A as shown in Figure 7.

![Figure 7. Machine cross-section (one sector) showing the location of coils A6, A4 and A2 in the stack on rotor Pole A.](image)
All other rotor field coils were modelled assuming a uniform current density at the rated field current to accurately model magnetic conditions in the field coil region. Machine nominal rated conditions were applied with a field current of 49 A, full load stator current of 577 A at almost 1.0 pf with an assumed coil temperature of 27 K. It was expected that the top double coil A6 would determine the critical current as it is exposed to the highest magnetic field magnitude and perpendicular field angle (to the tape) in the machine as shown in the magnetic flux density plot in Figure 8.

A plot of the auxiliary variable $P_i$ for the top and bottom layer of the double pancake coil A6 is shown in Figure 9 and 10 respectively. The analysis shows that the top layer experiences a fairly even magnitude of magnetic field (1.45 T) and magnetic field angle across the coil from inner to outer turns. The turns in the centre area of the double pancake coil top layer determine the coil critical current $I_{coil}$ for the machine.

A summary of the model results for the three coils are shown in Table 2 below. The effective critical current $I_{coil}$ of the machine under machine rated conditions at 27 K calculated by the model is 53.2 A for coil A6 which is within 9% of the nominal operating current (48.95 A). As expected coil A6 has the lowest critical current due to the highest magnetic field and less favourable field orientation compared to the other coils.

3.4. Comparison of $I_{coil}$ model with test measurements under operating conditions

Measurements of the voltage drop and stability of the HTS rotor coils were undertaken at machine full load conditions for comparison with the model results. Tests were undertaken at
Table 2. Model results for Pole A coils A2, A4 and A6.

| Coil   | $I_c$ (model) MAX criteria (1 $\mu$V cm$^{-1}$) | $I_c$ (model) SUM criteria (0.2 $\mu$V cm$^{-1}$) |
|--------|-----------------------------------------------|-----------------------------------------------|
| A6 (top) | 53.2 A                                         | 49.5 A                                         |
| A4 (middle) | 56.3 A                                         | 52.6 A                                         |
| A2 (lower) | 58.8 A                                         | 55.4 A                                         |

QUT test facility [20] in Brisbane Australia as shown in Figure 11. Indirect cooling of the rotor HTS coils is provided by Cryomech AL330 GM cold head connected to a rotor neon (Ne) thermosyphon cooling system [21]. The cryocooler temperature controller nominal setpoint for the test was 27 K. Rotor coil voltages and temperatures measurements are connected to a wireless telemetry system and logged along with other key data with the machine in operation.

We first examined the behaviour of the rotor HTS coil during ramping of the field current under machine no-load conditions. The rotor field current was ramped from zero to 5 A, 10 A, 15 A, 25 A, 35 A, 45 A, 47 A, 48 A and 49 A at a nominal rate of 0.05 A s$^{-1}$. Figure 12 shows a typical trace of the temperature and voltage on the double pancake field coil (A6) during the current ramping. The temperature trace is curved with each ramp as the $n$ value of the early Bi-2223 tape used in the machine is small and begins to exhibit a small resistance above 10 A. At each current ramp level the coil temperature reaches a thermal equilibrium. That is the cooling capacity of the cryocooler balances the thermal losses from the coil.

Extended operational load tests were then undertaken with the HTS1 machine in both generator and motor mode. In a test sequence shown in Figure 13 the machine was cycled...
from generator to motor mode with loading up to 375 kW with a constant field current of 49 A over a three hour period.

A rotor coil temperature and voltage trace for HTS1 rotor coil A6 during the load sequence tests is shown in Figure 14. During ramping, at rated load and under the load sequence tested the HTS1 rotor coils were stable and the double pancake coil A6 voltage drop measured up to 3.52 mV steady state, equivalent to a voltage drop per unit length in the coil of 0.196 µV cm\(^{-1}\) at rated field current of 49 A.

A summary of rotor coil voltage measurement test results for double coils A6, A4 and A2 during the load sequence tests at rated field current of 49 A are shown in Table 3.

| Coil  | \(I_{field}\) (test) | Coil Voltage (test) | Coil Voltage per Unit Length |
|-------|---------------------|---------------------|-----------------------------|
| A6 (top) | 49.0 A | 3.52 mV | 0.196 µV cm\(^{-1}\) |
| A4 (middle) | 49.0 A | 7.07 mV | 0.179 µV cm\(^{-1}\) |
| A2 (lower) | 49.0 A | 1.80 mV | 0.036 µV cm\(^{-1}\) |

The voltage drop per unit length for double coil A6 is within the expected range of the critical voltage versus current curve at the rated field current and in good agreement with the model which with a voltage drop per unit length criteria of 0.2 µV cm\(^{-1}\) predicts a current of 49.4A (an error of +1% with respect to test field current of 49A).
4. Conclusions
In this paper we have extended application of the self-consistent model for the process of assessing the effective $I_c$ of Bi-2223 pancake coils in self-field and in the applied field of a HTS synchronous machine.

We first employed the numerical method to examine the pancake coil performance in self-field at 77 K. The effective $I_c$ calculated by the model was in good agreement (maximum error of 4\% for the cases examined) of the original pancake coil test measurements. In addition to the magnitude of $I_c$ the model results highlight the influence of the anisotropic $J_c(B,\theta)$ of the Bi-2223 superconductor on determination of the location of the turns with a coil which develop a critical electric field. For the coils modelled, whilst the magnitude of the magnetic field is highest at the inner turn, the orientation of the field to the tape strongly determines the parts of the coil which develop a critical electric field. If we associate $I_c$ with the current the machine can carry without quench, this information is important at the machine / coil electromagnetic design stage as well as for selection of voltage tap points for coil quench detection systems.

The model was then employed to calculate the $I_c$ for three separate double pancake coils in the applied field of a HTS synchronous machine rotor at rated load conditions. The effective $I_c$ calculated by the model for the top double pancake coil which is exposed to the most onerous magnetic field in the machine was 53.2 A and approximately 9\% above the nominal rated field current of 48.95 A. The voltage drop per unit length measured across the coil at rated field current under full load conditions during the test was in good agreement with the expected voltage on the critical voltage versus current curve at the rated field current. Again if we associate $I_c$ with the current the machine can carry without quench, this information is important for determining safe operating margins.

As a final note, it is worth mentioning that when the HTS1 demonstrator was designed (circa 1999) 1G Bi-2223 conductor and measurements were at a basic technology level and broad empirical scaling rules were applied in the design of the machine for the superconductor temperature and magnetic field magnitude and angular dependence. Through modern numerical techniques and quality superconductor manufacture with accurate performance data it is possible to design and optimise the $I_c$ of the superconductor for economy as well as to ensure the safe and reliable operation of a superconducting machine.

Acknowledgments
The research project is part of the QUT, Australian Defence Science and Technology Group (DST Group) and Siemens joint research agreement to advance the use of HTS technologies in maritime applications.

References
[1] Klaus G, Wilke M, Frauenhofer J, Nick W and Neumüller H W 2007 Design challenges and benefits of HTS synchronous machines Power Engineering Society General Meeting, 2007. IEEE (IEEE) pp 1–8 URL http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=4275522
[2] Wilson M N 1987 Superconducting Magnets Monographs on Cryogenics (Oxford, New York: Oxford University Press) ISBN 978-0-19-854810-2
[3] Zhang M, Kim J H, Pamidi S, Chudy M, Yuan W and Coombs T A 2012 Journal of Applied Physics 111 083902 ISSN 00218979 URL http://scitation.aip.org/content/aip/journal/jap/111/8/10.1063/1.3698317
[4] Xia J, Bai H, Lu J, Gavrilin A V, Zhou Y and Weijers H W 2015 Supercond. Sci. Technol. 28 125004 ISSN 0953-2048 URL https://doi.org/10.1088%2F0953-2048%2F28%2F12%2F125004
[5] Zermeño V, Sirios F, Takayasu M, Vojenciak M, Kario A and Grilli F 2015 Supercond. Sci. Technol. 28 085004 ISSN 0953-2048 URL http://stacks.iop.org/0953-2048/28/i=8/a=085004
[6] Frank M, Frauenhofer J, van Hasselt P, Nick W, Neumüller H W and Nerowski G 2003 IEEE Transactions on Applied Superconductivity 13 2120–2123 ISSN 1051-8223 URL http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=1212037
[7] Han Z, Bodin P, Wang W G, Bentzon M D, Skov-Hansen P, Goul J and Vase P 1999 *IEEE Transactions on Applied Superconductivity* 9 2537–2540 ISSN 1051-8223

[8] Nick W, Nerowski G, Neumüller H W, Frank M, van Hasselt P, Frauenhofer J and Steinmeyer F 2002 *Physica C: Superconductivity* 372–376 1506–1512 ISSN 09214534 URL http://linkinghub.elsevier.com/retrieve/pii/S0921453402010699

[9] Wang W G, Han Z, Skov-Hansen P, Goul J, Bentzon M D, Vase P and Liu Y L 1999 *IEEE Transactions on Applied Superconductivity* 9 2613–2616 ISSN 1051-8223

[10] Vase P, Flükiger R, Leghissa M and Glowacki B 2000 *Supercond. Sci. Technol.* 13 R71 ISSN 0953-2048 URL http://stacks.iop.org/0953-2048/13/i=7/a=201

[11] Rhyner J 1993 *Physica C: Superconductivity* 212 292–300 ISSN 0921-4534 URL http://www.sciencedirect.com/science/article/pii/092145349390592E

[12] Grilli F 2016 *IEEE Transactions on Applied Superconductivity* 1–1 ISSN 1051-8223, 1558-2515 URL http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=7387708

[13] Majoros M, Glowacki B A and Campbell A M 2001 *Supercond. Sci. Technol.* 14 353 ISSN 0953-2048 URL http://stacks.iop.org/0953-2048/14/i=6/a=309

[14] Petrov A N, Pilgrim J A and Golosnoy I O 2019 *Physica C: Superconductivity and its Applications* 557 33–40 ISSN 0921-4534 URL http://www.sciencedirect.com/science/article/pii/S0921453418300613

[15] Gomory F, Souc J, Vojenčák M and Klinčok B 2007 *Supercond. Sci. Technol.* 20 S271–S277 ISSN 0953-2048 URL https://doi.org/10.1088%2F0953-2048%2F20%2FS271

[16] COMSOL Multiphysics® Modeling Software URL https://www.comsol.com/

[17] Bianchi N 2005 *Electrical machine analysis using finite elements* Power electronics and applications series (Boca Raton, FL: Taylor & Francis) ISBN 978-0-8493-3399-6 oCLC: ocm57694820

[18] Blatter G, Geshkenbein V B and Larkin A I 1992 *Phys. Rev. Lett.* 68 875–878 URL https://link.aps.org/doi/10.1103/PhysRevLett.68.875

[19] Wimbush S C, Strickland N M and Long N J 2015 *IEEE Transactions on Applied Superconductivity* 25 1–5 ISSN 1051-8223

[20] O’Brien P and Taylor R 2019 *IEEE Transactions on Applied Superconductivity* 1–1 ISSN 1051-8223

[21] Frank M, Frauenhofer J, Gromoll B, Hasselt P v, Nick W, Nerowski G, Neumüller H W, Haefner H U and Thummes G 2004 Thermosyphon Cooling System for the Siemens 400kw HTS Synchronous Machine *AIP Conference Proceedings* vol 710 (AIP Publishing) pp 859–866 URL http://scitation.aip.org.ezp01.library.qut.edu.au/content/aip/proceeding/aipcp/10.1063/1.1774764