APP1-1

Design and Test Results of a Quench Protection Circuit for a HTS Ship Propulsion Motor

Yohei Murase[1], Mitsuru Izumi[2], Tamami Oryu[1], Minoru Yokoyama[1], Katsuya Umemoto[1], Toshiyuki Yanamoto[1,2]

Kawasaki Heavy Industries, Ltd.[1]
Tokyo University of Marine Science and Technology[2]

When a cryogenic cooling system for a high-temperature superconducting (HTS) motor stops due to blackout, mechanical failure, or others, the temperature of the HTS coils rises. If the operating current of the HTS coils are left despite the temperature rising of the HTS coils, a quench occurs in the HTS coils. Because HTS coils have low thermal conductivity, the quench instantaneously generates a hotspot which locally becomes high temperature and causes irreversible damage to the HTS coils. In order to protect the HTS coils from the damage caused by the quench, it is necessary to quickly attenuate the operating current of the HTS coils and suppress the generation of the hotspot after the stop of the cooling system.

In this study, we propose a novel configuration of a quench protection circuit for a HTS ship propulsion motor that protects the HTS coils from an unexpected stop of its cooling system. This quench protection circuit consists of conductor plates placed adjacent to the HTS coils and dump resistors placed at the normal temperature part and the low temperature part. With this configuration, it becomes possible to more effectively and quickly attenuate the operating current of the HTS coils by the mutual induction between the HTS coils and the conductor plates. In addition, since the energy of the HTS coils can be dispersedly absorbed by this configuration, the dump resistors can be made small size and become easy to mount on a HTS ship propulsion motor. We have designed with numerical simulations and fabricated the quench protection circuit for the one HTS field pole of the 3 MW HTS motor developed by Kawasaki Heavy Industries. The fabricated protection circuit was tested experimentally and its effect was validated. By comparing the design results with the test results, we have confirmed that our design has high accuracy.

This work includes the results supported by the New Energy and Industrial Technology Development Organization (NEDO).

Keywords: Quench Protection, HTS motor, HTS field pole, HTS coil

APP1-2

Optimal Design of a Superconducting Motor for Electric-drive Aeropropulsion Based on Finite-Element Analysis and Genetic Algorithm

*Weilu Kong[1], Yutaka Terao[2], Hiroyuki Ohsaki[2]

Department of Electrical Engineering and Information Systems, Graduate School of Engineering, University of Tokyo, Japan[1]
Department of Advanced Energy, Graduate School of Frontier Sciences, University of Tokyo, Japan[2]

Electric-drive Aeropropulsion (EA) is one of the key technologies in design of future aircrafts because the electric motor drive has high efficiency and the EA would reduce both operational cost and pollutant emission [1]. However, it would have some problems like the cruising range and payload.To solve these issues, the introduction of superconducting rotating mashines (motors and generators) have been proposed [2] because it will allow integration of electric propulsion within the very stringent weight and volume constraints. Superconductors can carry electric current at high current density with quite low resistance thus enabling light machines. According to previous researches, a superconducting motor is supposed to achieve power density comparable to turbine engines in excess of 10 - 20 kW/kg [3]. And, to improve the power density and to reduce loss simultaneously, the optimization of the design is indispensable. In this paper, a 3.613 MWsuperconducting motor design optimized by the Finite-Element Analysis (FEM) and the Multi-Objective Genetic Algorithm (MOGA) for EA is presented. $YBa_2Cu_3O_{7\text{-}\delta}$ field windings in an air-core rotor construction and MgB_2 or copper armature windings in the stator without iron teeth are assumed in the synchronous motor design. Analysis formula and Finite Element Method (FEM) analysis have been used in the first-step design to acquire an initial model and constraint conditions. The FEM+MOGA has been used in the optimization to acquire the design of a motor with a good balance of power density, loss and torque ripple.

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[2] Luongo C A, Masson P J, Nam T, Mavris D, Kim H D, Brown G V, Waters M and Hall D 2009 *IEEE Trans.Appl. Supercond.* **19** 1055-1068
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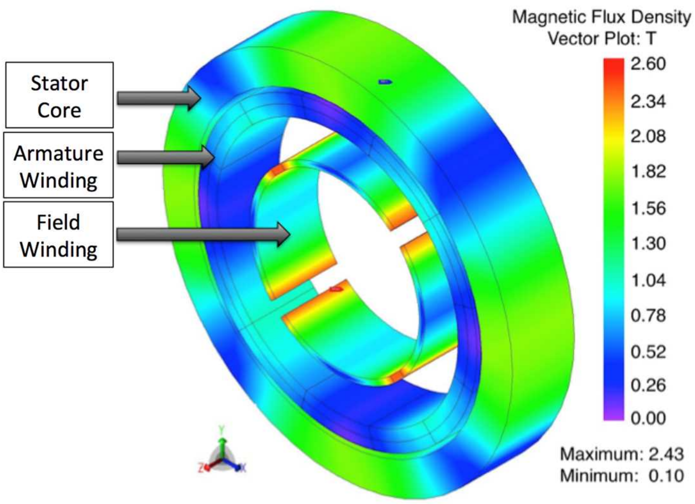

Fig. 1 Magnetic flux density distribution of the designed motor.

Keywords: Superconducting motor, Electric-drive aeropropulsion, Optimal design, Finite-element analysis

APP1-3

Design and Electrical Performance of Prototype Winding for Closed-Circuit Magnetization

*Keita Tsuzuki[1], Yunosuke Suzuki[1], Sho Yamamura[1], Dai Oikawa[2], Takehiko Tsukamoto[2], Hiroya Ando[1]

Department of Information and Computer Engineering, National Institute of Technology, Toyota College.[1]
Department of Electrical and Electronic Engineering, National Institute of Technology, Toyota College.[2]

Innovative magnets brought by High-temperature superconductor (HTS) winding and bulk is an enabling technology to many advanced applications. For industrial application, HTS magnet provides smaller and more efficient motors and generators thanks to intensified magnetic flux.

Bulk HTS material which can provide strong magnetic field in compact space is effective to achieve high power density within the rotating machine. Our group has designed bulk HTS motor with Closed-Circuit magnetization (CCM) which is novel method to trap magnetic flux to field pole for radial gap rotating machine.

In this study, the design, concept and capabilities of the HTS armature coil which posess co-existence for magnetizing coil is demonstrated. The geometry for prototype machine was evaluated and optimized by using FEA in our work.

For further development and evaluation of feasibility about CCM with the rotating machine structure, prototype windings were manufactured by using Bi2223 HTS wire. To make the construction of armature coil simplified, trapezoidal shape with double pancake winding was adopted.

Electrical performance of the HTS prototype winding under DC/AC operation was measured. Prototype HTS windings were tested under various temperature including standard 77K self-field measurements and cryo-cooled condition. Finally, we also discuss in detail the implementation of armature construction and operating condition on CCM for our HTS rotating machine by referring measured parameter and FEA results.

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[2]Y. Suzuki and K. Tsuzuki, Consideration of captured magnetic flux density in cylindrical HTS using finite element method, Tokai-Section Joint Conference on Electrical, Electronics, Information and Related Engineering, Po2-9, 2016

[3]K. Tsuzuki et al., Magnetic Field Analysis of High-Temperature Superconductor Field Pole Using Convergence-Magnetized Method with Closed Magnetic Circuit, Abstracts of CSSJ Conference, Vol.94 1C-p09, 2017

Keywords: Armature winding, Synchronous motor, Bi2223, magnetization coil

APP1-4

Design and Analysis of Air-Core Superconducting Generator for Wind Power Applications

*Han-Wook Cho[1], Matthew Feddersen[2], Kiruba Haran[2]

Chungnam National University[1]
University of Illinois at Urbana-Champaign[2]

In the movement towards reducing CO_2 emissions and our dependence on fossil fuels, wind power is considered one of the main technologies in delivering renewable energy to the world. With the introduction of a technology such as superconducting(SC) coils in to wind generator design, new spaces open up for novel topologies and implementations. One such topology is the actively-shielded air-core SC machine described in previous work [1]. Fig. 1(a) shows the component of the actively shielded air core design. The 2D cross section highlights the effect of the shielding coils on the magnetic field outside the machine. An example CAD model of a 4.8m diameter air-core SC wind generator is shown in Fig. 1(b). In Table I, design choices are presented for a variety of possible generators utilizing are air-core superconducting topology. The main differentiating factors between the designs are in their intended application and power rating, both of which result in different design choices. Even with this limited first-pass analysis, the 10 MW air-core design displayed a decreased active length when compared to the reference design, leading to a decrease in both copper and SC weight. While not explicitly analyzed, the lack of iron in the air-core machine also significantly decreases the overall machine weight.

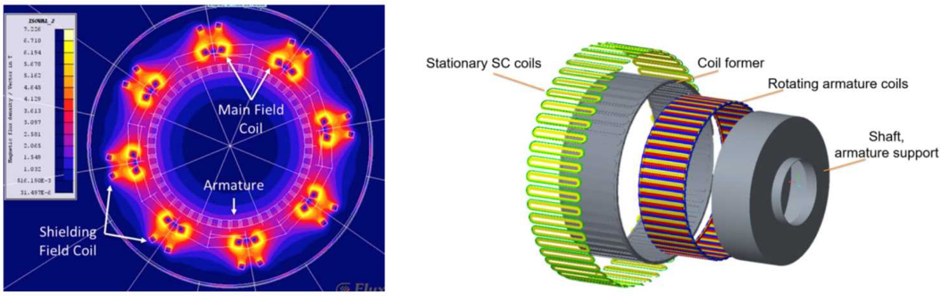

Fig. 1 (a) Fig. 1 (b)

Table I.

		Reference Design	Air-core design 1	Air-core design 2
Application		Offshore	Offshore	Land
Rated power	(MW)	10	10	6
Rated speed	(rpm)	10	10	10
Active length	(m)	1.88	1	1.5
Diameter	(m)	4.83	4.8	3.2
Pole count		36	52	34
Armature current density	(A/mm^2)	3.6	3.6	3.6
Armature copper depth	(mm)	127	127	127
SC coil material		NbTi	Nb_3Sn	Nb_3Sn
SC coil total length	(km)	720	380	300
SC coil total weight	(kg)	3840	1000	900
Armature copper weight	(kg)	9720	6000	5500

Fig. 1. (a) 2D FEA showing magnetic flux density distribution (b) Exploded view of air-core SC wind generator components.
Table I. Reference and final design parameters.

[1] K. Haran, D. Loder, T. O. Deppen, and L. Zheng, "Actively shielded , high field air-core superconducting machines," IEEE Trans. Appl., Supercon., vol.26, no.2,Mar. 2016, Art.ID.5202508.

Keywords: Air-core superconducting generator, wind power application, actively-shielded

APP1-5

Design of a Characteristic Evaluation Device for the Field Coil of Superconducting Wind Power Generator

*Changhyun Kim[1], Hae Jin Sung[1], MinWon Park[1], InKeun Yu[1]

Chang Won National University[1]

Globally, Superconducting (SC) wind power generator is being studied for having high capacity and compact volume of a wind turbine. Most of MW class SC wind power generators have characteristic of high capacity and low-speed machines, the load due to a very high torque affect the superconducting coils. In this case of generator get some problem that electromagnetic field and high torque from armature coils may cause damage to the coil. So, SC wind power generator need to analyze operating characteristic for superconductor field coil and stability in high magnetic field. That is mean, it is need to design the characteristic evaluation device for design verification and characterization before creating the entire SC wind power generator system.
This paper performed a characteristic evaluations device (CED) design for the field coil of 4MW, 10MW, 12MW SC wind power generator.
MagNet was used as a finite elements method analysis tool to design CED and its characteristics. This CED was simulated considering the field coil of 4MW, 10MW, 12MW Wind power generator. The CED is made like a vertical linear generator. It is composed of 2 pole field coil which is the rotor part of the wind generator and 1pole armature coil which is the stator part of the wind generator. The stator body falls freely about six meters next to the fixed 2 pole field coil. By crossing the superconducting coils and stator body be owing to gravity, generate capacity of 1pole SC wind power generator and it is possible to visually judge whether or not the superconductor coil is damaged by electromagnetic force.
As a result, when tested by the parameter value of a 12MW generator, the same result was obtained when comparing the results of the analysis of 12MW generator and the results of the characteristics evaluation device. The characteristic evaluations device will confirm the characteristic of field coil. This device can be evaluated whether field coils are usable for superconducting generators.

Keywords: superconducting, coil evaluation, linear generator, superconducting wind power generator

APP1-6

Design and thermal analysis of an HTS module coil for a 12 MW wind power generator

*Tat-Thang Le[1], Hae-Jin Sung[1], Byeong-Soo Go[1], Oyunjargal Tuvdensuren[1], Minwon Park[1], In-Keun Yu[1]

Changwon National University, Republic Of Korea[1]

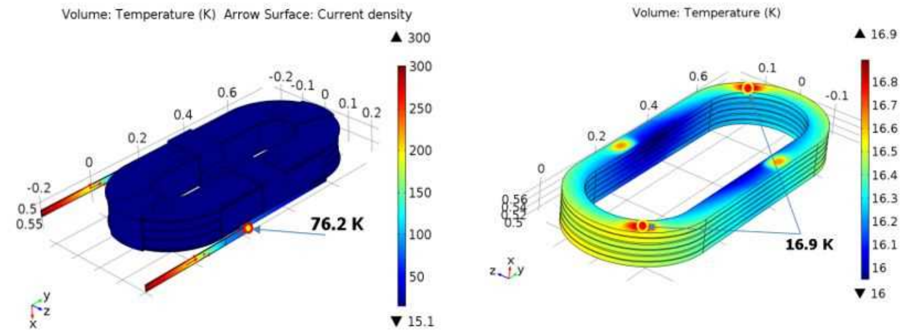

Fig 1.1 Temperature distribution in HTS coil

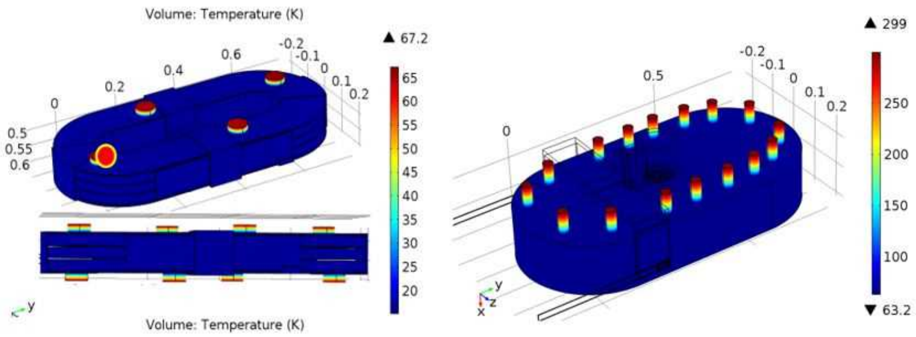

Fig 1.2 Temperature distribution in the supports

A large-scale high-temperature superconducting (HTS) wind power generator requires a huge vacuum vessel to cool the HTS coils together and needs high stability of the series connected multi-pole structure of the HTS coils. If one of the HTS poles fails to operate, the rest of the poles will stop working due to the series connection of the HTS coils. In order to avoid these weaknesses, an HTS generator module coil has been suggested, through which all the HTS poles can be structurally separated with a small vacuum vessel, and independent operation can be ensured with high reliability. A heat loss analysis considering the module structures is of importance for an effective design of the HTS module coil based generator. However, the heat loss analysis of a large-scale HTS generator or the module coil has rarely been studied and is becoming a new challenge. This paper deals with the design and thermal analysis of an HTS module coil for a 12 MW wind power generator.
Heat losses of the HTS module coil include radiation loss, eddy current loss of the structures of the coil bobbins, ac loss of the HTS magnet, conduction loss of the current leads and supports of the magnet, and Joule loss of the current leads and joint with the HTS magnets. The two-stage cryo-cooler of RDK-415D was used to achieve the operating temperature of 20 K. Current leads were designed optimally for reducing the conduction and Joule heat losses. The total heat losses of the HTS magnet module were analyzed using 3D finite elements program (FEM). The supports were located in the 1st layer and 2nd layer of the HTS module coil. The size of all of supports was calculated to estimate the conduction heat loss from outside to the 1st layer and between the 1st and 2nd layers.
The results of heat losses and temperature distribution were confirmed by using FEM program. As a result, the temperature of the magnet was achieved under the operating temperature of 20 K, and the total heat loss was less than the cooling capacity of the cryo-cooler. The results will be utilized for structure design of a large-scale HTS generator module coil.

Keywords: HTS wind power generator, HTS module coil, thermal analysis, two-stage cryo-cooler

APP1-7

Structural Design and Heat Load Analysis of a Flux Pump based HTS Module Coil for a Large Scale Wind Power Generator

*Oyunjargal Tuvdensuren[1], Haejin Sung[1], Byeong soo Go[1], Tat-Thang Le[1], Minwon Park[1], In-Keun Yu[1]

Changwon National University[1]

Abstract - Recently, high temperature superconducting (HTS) generators are suitable for large scale wind power systems. The superconducting generator typically requires a power supply, a current lead and a slip ring for transferring the DC current into the HTS coils. The current lead can be a bridge between the cryogenic environment and room temperature, which causes heat transfer loss. On the other hand, the flux pump (FP) is possible to supply DC current into the HTS coils of the generator without the heat transfer loads. However, a novel structural design and the heat load analysis considering the connection with the flux pump and the HTS coils are required for the HTS wind power generator.

This paper deals with a structural design and heat load analysis of a FP based HTS module coil for a 12MW wind power generator.

The structures such as HTS coil bobbins, coil supports, and the connection components between the flux pump and the HTS coils were designed. The conduction and radiation heat loads of the FP based HTS coils were analyzed using a 3D finite element method program considering the two-stage cryo-cooler (RDK-415D). The results of the FP based HTS coil of the generator were compared with a conventional current lead based HTS module coil.

As a result, the heat load of the FP, that is the sum of Joule heat and iron losses was 10.2 W. Therefore, the total head loads of the FP based HTS module coil were lower than the conventional current lead based HTS module coil. The structural design and heat load analysis results of the FP based HTS module coil can effectively be utilized to develop a large scale HTS wind power generator.

Keywords: Current lead, Flux pump, Heat load, Module coil