AP1-1-INV

High Power Superconducting Wind Generator

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General Electric[1]

The presentation discusses high-power superconducting wind generator that is being built at General Electric[1)]. The generator uses LTS (low temperature superconducting) field coils to create a minimum of 2 T magnetic field in the air gap. The generator is substantially lighter, more compact, and cost effective than other compared approaches. The generator promises significant cost and performance improvements versus conventional wind generators that are utilize permanent magnets. Major design decisions, trade-offs, options, conductor requirements, and electromagnetic features such as quench protection and cryogenic support options are discussed.

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Keywords: wind generator, low temperature superconductor, rotating machinery

AP1-2-INV

Test operation of 500 m /100 MW Ishikari high-temperature superconducting DC transmission line to demonstrate the required cost reduction and robustness for practical social applications

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Ishikari Superconducting DC Power Transmission System[1]
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Superconducting DC transmission (SCDC) can reduce power losses during transmission to one-tenth of the losses occurring duringconventional AC transmission. Therefore, it is expected to be a key technology for achieving carbon neutrality (CN). The advantages of SCDC are its ability to transmit power over long distances at a low voltage and the compact geometry of superconducting cables. Owing to their compactness, it is possible to install underground cables that are robust against natural disasters, such as typhoons and earthquakes, at low costs and with negligible environmental impact. SCDC is expected to address problems such as insufficient capacities in existing transmission lines that may result from the future increase in renewable energy use. Thus, innovative power networks can be developed.

The social implementation of SCDC, however, may require further preliminary research and the creation of a new business model based on the resulting database. As the first step in this process, this paper describe the results of the Ishikari Line 1 restart test conducted in September 2021 to collect basic data for cost reduction and improved efficiency and to confirm the equipment integrity after approximately 6 years of shutdown. Based on these results, we aim to promote the social implementation of SCDC by constructing a database for the quantitative evaluation of reliability, safety, and cost.

The Ishikari Superconducting DC Power Transmission System (I-SPOT) was established in January 2014 as a Collaborative Innovation Partnership (CIP) under the authority of the Ministry of Economy, Trade, and Industry (METI). Its objective is to implement research activities on SCDC and related technologies, including design, construction, and performance demonstrations at large-scale facilities. The Ishikari SCDC demonstration test facility was constructed in 2013 in Ishikari, Hokkaido, and comprises the world’s longest class of 500 m (Line 1) and 1000 m (Line 2) cable systems. Based on a 4 year demonstration test conducted on Lines 1 and 2 of the SCDC system, it was confirmed that SCDC can reduce the transmission loss to one-tenth of conventional AC transmission system losses. A key technology for this reduction was a recently developed ultra-low-loss cryogenic pipe, which achieved a heat loss of less than 1 W/m along the cable.

Using Line 1, which is a 500 m SCDC system (5 kA, 20 kV, 100 MW) installed underground, we successfully demonstrated the world's first power transmission from a solar power plant to an Internet data center in September 2015. After two comprehensive tests (cooling and energizing operations) in 2015, the operation of Line 1 was suspended for an extended period and was

restarted in September 2021, with neither cooling nor energizing conducted, while a vacuum was maintained inside the cryogenic pipe. During the shutdown period, a strong earthquake occurred (2018 Hokkaido Eastern Iburi Earthquake, September 6, 2018, maximum intensity of 7), and the Ishikari area experienced an intensity of 5 Lower. The restart operation confirmed the integrity and robustness of the facility, which had experienced a major earthquake and was shut down for approximately 6 years.

The main components of Line 1 are the cooling, insulation and vacuum, electrical, and measurement and monitoring systems. The interior of the cryogenic pipe was vacuumed, and liquid nitrogen flowed through two inner pipes (cable and return pipes). A superconducting cable was installed inside the cable pipe. Terminal cryostats were installed at both ends of the cryogenic pipe, and measurement signals, such as power, liquid nitrogen refrigerant, superconducting cable, and current lead voltage, were transmitted across low and room temperatures.

The procedure for the restart test was as follows: (1) vacuum evacuation of the cryogenic pipe, (2) initial cooling of the cable and return pipes (flow of low-temperature nitrogen gas), (3) circulation of liquid nitrogen using a refrigerator and circulation pump, (4) conduction of cooling and circulation tests, as well as various electrical tests, and (5) following completion of all tests, an increase in the temperature to room temperature and termination of the entire operation. During the restart test, cooling circulation and electrical tests were conducted under various operating conditions in addition to the rated conditions.

The integrity and robustness of all system components, including the SCDC main unit, chiller, control equipment, vacuum system, and measurement system, were confirmed. For superconducting cables, our results confirmed that autonomous uniformity of the current distribution occurs at the connections. These results are useful for replacing the Peltier current leads with normal current leads. The integrity of the superconducting cable was tested in terms of its capacitance, insulation resistance, and DC withstand voltage. The superconducting state was maintained under the rated conditions, and the cable was energized in a stable manner. To improve the chiller operation efficiency, the overall system could be cooled using the turbo Brayton chiller alone; accordingly, partial load conditions that reduced the chiller efficiency could be observed. It was also demonstrated that SCDC can be operated by circulating liquid nitrogen at high temperatures and low flow rates. Optimization of the refrigerant conditions and high-efficiency operation of the refrigeration equipment are also possible.

These results suggest that, with appropriate maintenance, the SCDC system can sufficiently maintain normal operation characteristics for several decades in practical applications.

Keywords: High Temperature Superconductor (HTS), DC Transmission, long distance transmission, carbon neutral (CN)

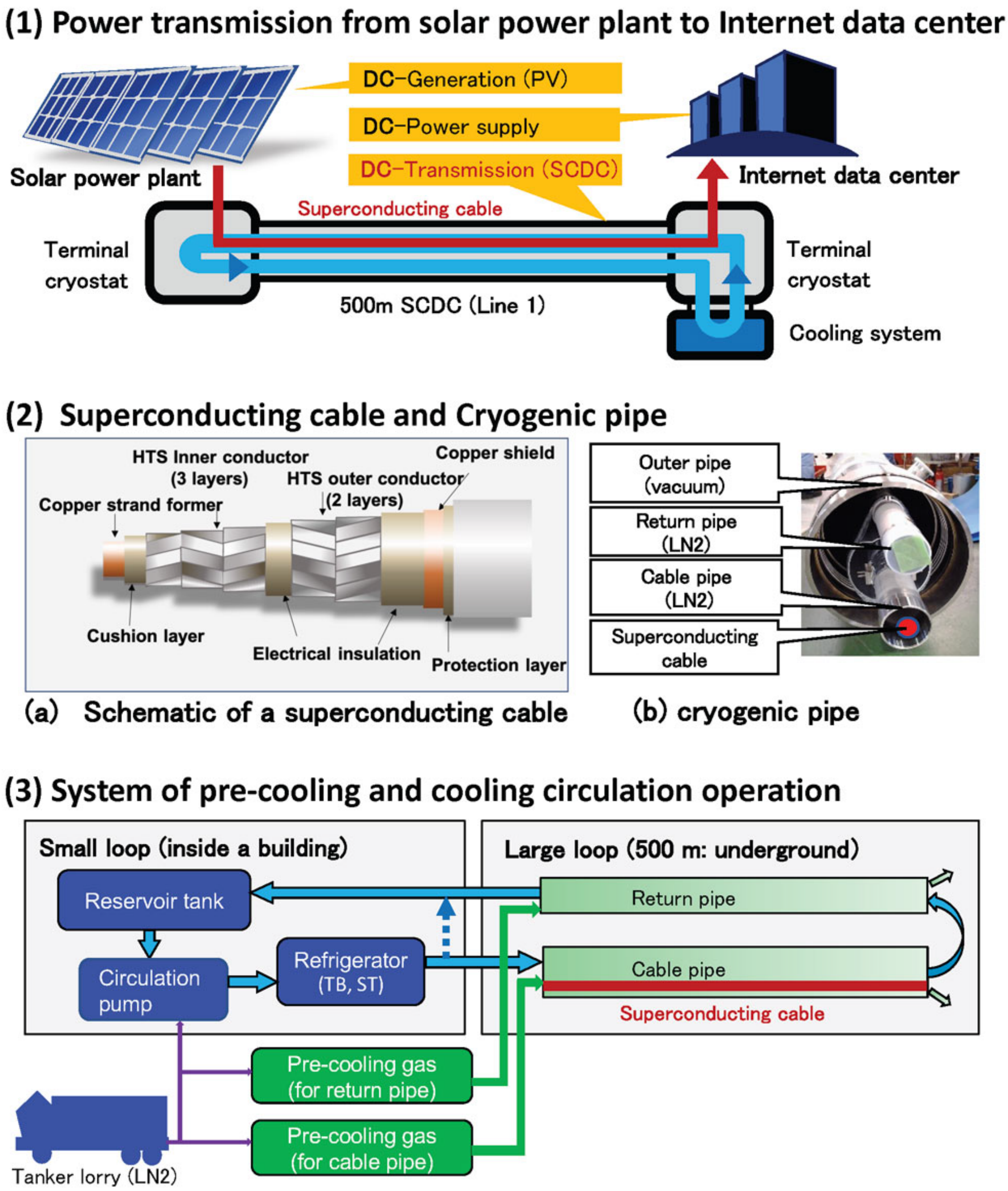

Figure Ishikari high-temperature superconducting DC transmission system (Line 1)

AP1-3-INV

Application Possibility of SMES to Electric and Hydrogen Hybrid Energy Storage System for Large-Capacity Renewable Energy Generation

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The world's energy consumption is increasing due to the growth of the world's population and the economic growth of developing countries, and most of that energy is dependent on fossil fuels. To solve this energy problem, the introduction of renewable energy sources that do not affect the environment is being promoted. However, one of the major problems with renewable energy sources is the fluctuation of output power. It is necessary to establish an output fluctuation compensation function, which is independent of the commercial grid, to expand the introduction of renewable energy sources.
To compensate for output fluctuations of renewable energy sources, energy storage devices play an important role which can charge the surplus generated power and discharge it when the generated power is insufficient for demand. The energy storage devices must have high capacity and durability to provide stable power for a long time and must be able to respond quickly to compensate the rapid power fluctuations in renewable energy sources. High energy density is also required. However, there is no energy storage device that satisfies all these requirements. We have proposed a “Hybrid Energy Storage System (HESS)” as an energy storage system that consists of a “hydrogen system” with high capacity and high energy density and an “electric double layer capacitor (EDLC)” with superior responsiveness and durability.
To expand the introduction of renewable energy in the future, it is necessary to increase the capacity of the HESS. We proposed to introduce the SMES, which has the advantage of scale, to the power storage device of the larger-capacity HESS. However, it has been reported in previous studies that the fluctuation compensation performance of the SMES is lower than that of the EDLC and other devices. Thus, to apply the SMES to the large-capacity HESS for future expansion of renewable energy sources, this study investigated the application possibility of the SMES to the HESS by examining the system configuration and operation control method that can improve the fluctuation compensation performance of the SMES.
We first simulated that the SMES is installed in a power supply system with the rated power of photovoltaic power generation of 20 kW and investigated the effective system configuration and operation control method for improving the fluctuation compensation performance of the SMES. As a result, we identified an effective system configuration in which the SMES and a capacitor are connected in parallel, and a bidirectional DC-DC converter is installed between the DC bus and the SMES system. Furthermore, as an operation control method, we found that the passive voltage control method was effective, which controls the voltage at both ends of the capacitor by controlling the amount of input and output energy of the SMES. The bidirectional DC-DC converter controls the amount of input and output energy of the SMES system while controlling the DC bus with constant voltage. The fluctuation compensation performance was significantly improved compared to the conventional SMES system by applying the proposed system configuration and operation control method.
The effectiveness of the proposed system configuration and operation control method in the large-scale renewable energy power supply system was also investigated. However, in the large-scale system, high fluctuation compensation performance could not be achieved with the proposed system configuration and operation control method for the 20 kW test system. This

was due to the poor response and small amount of stored energy of the superconducting coil.
We proposed a SMES system with superconducting coils arranged in parallel as the system configuration method that can improve the response and stored energy of the superconducting coils. As a result, the SMES system with superconducting coils arranged in parallel achieved the same level of high fluctuation compensation performance as the EDLC. It is necessary to select the number of paralleled superconducting coils and the inductance of the superconducting coils considering the scale of the HTSS system within the cost constraint.
This study established a system configuration and operation control method of the SMES that is effective for high fluctuation compensation performance of large-scale renewable energy power supply systems for the future expansion of the introduction of renewable energy.

AP1-4

Demonstration and thermal equilibrium analysis of a 10 kJ capacity energy storage coil made of MgB2 with liquid hydrogen indirect cooling

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Renewable energy consists of solar power and wind power, and is attracting attention as a next-generation energy source due to its large effect in reducing carbon dioxide emissions. However, renewable energy is dependent on natural conditions such as weather. Therefore, the output is unstable and difficult to follow electricity demands, causing restriction of increasing capacity originated from the renewables. In order to solve this problem, it is necessary to store power from renewable energy and absorb and smooth out fluctuations in output.

To achieve this, we have proposed and demonstrated an Advanced Superconducting Power Conditioning System (ASPCS) that combines a superconducting magnetic energy storage device (SMES), a fuel cell generator, and an electrolyzer. ASPCS is a system that splits the fluctuating output power into long-term and short-term components and compensates for a well-controlled power. When there is an oversupply of power generated by renewable energy, the surplus is stored as hydrogen by electrolyzing water with an electrolyzer (EL). Also, when the generated power is insufficient, the hydrogen is supplied to the fuel cell to make up the power-shortage, while high-frequency power fluctuations that cannot be absorbed by fuel cells are leveled by SMES with the short-time charge and discharge ability. This system could be a solution to the enhancing utility grid stability and effective use of renewable energy. SMES that plays the most important rule in ASPCS, is a device that uses superconducting coils to store electric power with extreme high efficiency, due to not converting it into other forms of energy or degrading with the number of cycles.

At present, hydrogen energy is attracting attention as a clean energy that does not emit greenhouse gases when used, and this system also uses hydrogen energy as its central axis. Hydrogen has a boiling point of 20 K at 1 atm and has not been used as a refrigerant due to the danger of wide explosion limits. Besides evaporation during transportation is not negligible. We also have been proposed the effective use of boil-off gas by providing the gas as an energy source for electricity generation from the fuel cells, as well as utilizing the cold heat for cooling Joule heat generated along the transmission lines.

Our research team used MgB2 as a superconducting material to fabricate coils. Because critical temperature is around 39 K, it shows superconducting properties when cooled with liquid hydrogen. This will combine an environmentally friendly power generation system with a liquid hydrogen station for fuel cell vehicles to create an economical, ultra-low-carbon system. In addition, MgB2 can be easily made into a wire following conventional powder-in-tube technology with low cost and the product is light weight.

Liquid hydrogen is flammable and must be operated in a safe manner. For this purpose, we have introduced an indirect liquid hydrogen cooling system based on thermosiphon circulation technology that completely separates the combustible liquid and the power. Cooling by

thermosiphon is highly reliable because there is no drive equipment such as a pump. In the current phase of the project, we fabricated a 10 kJ SMES coil system indirectly cooled by liquid hydrogen and demonstrated it both at DC and with varying current at several ramp rate conditions.

In this report, we describe the evaluation of transport properties and losses by changing the current as well as the contact resistance between the coil and terminals. We also use computer simulations with heat balance equations to evaluate and lead to the design of large-capacity future energy storage such as the MJ class, which is comparable to conventional NbTi SMES.

Keywords: superconductivity, MgB2

AP2-1-INV

Design, fabrication and testing of a superconducting electrodynamic suspension magnet with coated conductor tapes

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Coated conductor magnet wound with coated conductor tapes, as the onboard magnet of electrodynamic suspension (EDS) train, is deemed promising due to its relatively high operating temperature, low cooling cost, and good mechanical tolerance, making the liquid-helium-free high-temperature superconducting (HTS) EDS train possible. In order to promote the progress of HTS EDS train, we designed, fabricated and tested an HTS EDS magnet. The HTS magnet is designed with the comprehensive considerations of the electromagnetic calculation, thermal-mechanical coupling analysis, as well as the heat load estimation. A radiation shield was used to reduce the heat leakage, enabling the cryogenic system to provide a better low-temperature environment for the magnet. Through a deliberate design, the magnet was fabricated, including two HTS coils and the tailored cryogenic system. It was proven that the magnet can be cooled to below 15 K; besides, the magnet has been successfully charged to 240 A. Afterwards, the electromagnetic interaction between the magnet and ground coils was investigated with both simulation and experiment. To measure the three-dimensional magnetic forces between the magnet and ground coils, a static test platform was built with an analytical-experiment coupling method. Moreover, an experimental rig was established and utilized to clarify the thermal performance of the magnet when subjected to the travelling magnetic field generated by the ground propulsion coils. The present study will provide useful implications for the design and performance evaluation of onboard HTS magnets in EDS train.

Keywords: coated conductor, electrodynamic suspension (EDS), conduction-cooled magnet

AP2-2-INV

Development of 400 kW class induction heating device for aluminum billets using HTS magnet

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High frequency AC induction heating methods are commonly used for billet heating in aluminum hot extrusion processes. In the aluminum industry, development of highly efficient and fast heating methods of aluminum billets is expected, since the energy efficiency of conventional high frequency AC induction heating of aluminum billets using water-cooled Cu coils is generally low [1]. The induction heating by rotating the aluminum billet in strong DC magnetic field called DC induction heating [2, 3] has been proposed and its high efficiency has also been demonstrated. By applying HTS magnets for the DC induction heating, it is possible to significantly improve the heating capacity and the energy efficiency compared to the conventional induction heating method. We have been developing an aluminum billet heater using a HTS magnet for the extrusion processes. The target heating capacity for heating a 6 inch x 500 mm aluminum billet from 20 degrees Celsius to about 500 degrees Celsius within 60 seconds is 400 kW. The schematic overview of our billet heater is shown in Fig. 1(a).

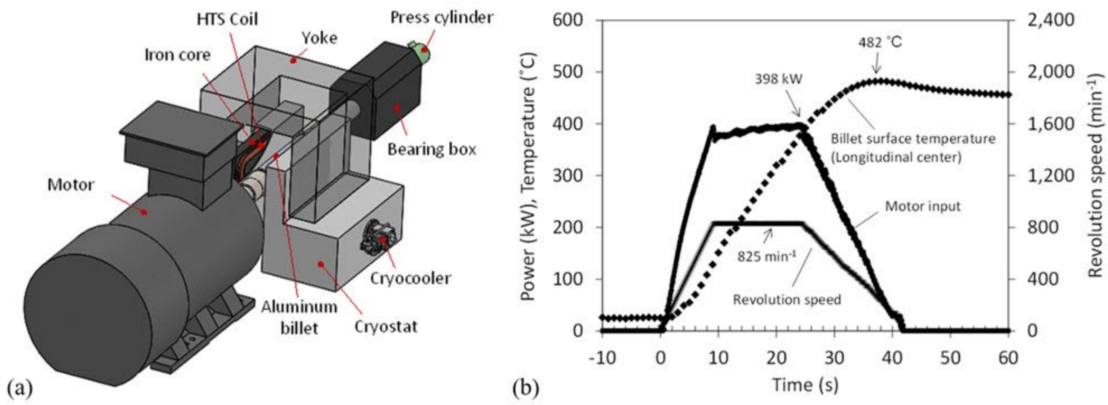
This demonstration machine consists of the drive unit of aluminum billet, the HTS magnets and an aluminum billet grasping mechanism. The aluminum billet is rotating by using the inverter-fed induction motor of 400 kW output. The HTS magnet with an iron core is used to improve the efficiency of the magnetic circuit. The HTS coil is wound directly around the iron core. This part is located in a cryostat and cooled to cryogenic temperature. The backs of the two sets of HTS coils are connected by a yoke placed at room temperature. This structure can effectively save the necessary amount of HTS tapes in the coils. The detail design and test results of the HTS magnet has been reported in [4]. The aluminum billet grasping mechanism transmits a rotational force from the drive unit to the aluminum billet. In our billet heater, the maximum heating capacity is 400 kW at 900 min^{-1}, therefore the necessary transmit torque to the billet is about 4.2 kN·m. To transmit this large torque, the grasping system needs to press an aluminum billet with a force of hundreds of kN (around 500 kN). Since the mechanical hardness of aluminum strongly affects the grasping property, we measured the temperature dependence of mechanical properties of aluminum. According to this measurement result, the grasping force control system was developed. Using the demonstration machine, the heating test was conducted on an aluminum billet (A6063) with 155 mm in diameter and 500 mm long. Fig. 1(b) shows the time traces of billet temperature, revolution and input power to the drive motor when the coil current was 180 A (096 T at center). As shown in Fig. 1(b), the billet temperature reached about 482 °C after 42 seconds. The maximum motor input was about 398 kW. From the results of heating tests, we found that the energy efficiency including the refrigeration power was about 74 %.

In the presentation, the detail of the design and fabrication of our test apparatus is summarized and the R & D status are reported.

Fig. 1. (a) Schematic diagram of the aluminum billet heater under developing (b) Result of heating test

[1] P. G. Simpson, INDUCTION HEATING – Coil and System Design -, McGraw-Hill, 1960.
[2] M. Fabbri, M. Forzan, S. Lupi, A. Morandi, and P. L. Ribani, "Experimental and Numerical Analysis of DC Induction Heating of Aluminum Billets," IEEE Trans. Magn., vol. 45, no. 1, pp. 192-200, Jan. 2009.
[3] R. Araneo, F. Dughiero, M. Fabbri, M. Forzan, A. Geri, A. Morandi, S. L. Lupi, P. L. Ribani, and G. Veca, "Electromagnetic and thermal analysis of the induction heating of aluminum billets rotating in DC magnetic field," COMPEL Int. J. Comput. Math. Electr. Electron. Eng., vol. 27, no. 2, pp. 467-479, 2008.
[4] T. Ito, Satoshi Fukui, Hiroshi Kawashima, Yasuhiro Ogata, Mitsuho Furuse, Tomonori Watanabe, Shigeo Nagaya, and Jun Ogawa: "Fabrication and Test of HTS Magnet for Induction Heating Device in Aluminum Extrusion Processing", IEEE Transactions on Applied Superconductivity, Vol.32, No.4, (2022), Art. no. 4600205.

Keywords: HTS magnet, Induction heating



AP2-3

Design Study of an HTS Linear Power Generator Suitable for Wave Energy Power Generation

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In this presentation, we introduce an ocean energy power generator using high-temperature superconducting (HTS) bulks. HTS bulks can trap high magnetic flux density over ten times higher than the maximum magnetic field produced by permanent magnets. Ocean energy power generation using seawater, which has a density 840 times higher than that of the atmosphere, requires power generation devices to be driven at low speeds with high torque. HTS bulks are suitable for power generation because they generate a strong magnetic field. We have conceptually designed a linear generator for wave energy converter using HTS bulk field poles. The large forces generated by ocean waves often place significant loads on the power generation mechanism, requiring them to be combined with the damper. In linear generators for wave power converter that include HTS bulk field poles, the large electromagnetic forces generated by the high magnetic fields associated with the HTS bulk magnetic poles will replace that damper, effectively driving the linear generator's translator power generation system with low mechanical losses. For this reason, in this study we designed a new linear power generation structure for wave energy converter. The proposed linear structure utilizes $(Re)Ba_2Cu_3O_{(7-\delta)}$ HTS bulks for field pole. The HTS bulks were modelled numerically using a finite-element model based on the *H*-formulation and implemented in COMSOL Multiphysics software. Since the proposed linear generator will be used for power take-off of a wave energy converter, we plan to use a buoy as a primary capture of the kinetic energy from the vertical component of ocean waves speed. But, since the buoy is connected to the translator power generation system of the linear generator, the speed of the translator power generation system is also low as the ocean waves slow down vertically. In order not to reduce its power output, the reciprocating speed of the translator must be increased despite the slow buoy oscillation since output power is a function of the speed and force of the translator power generation system. For this reason, we devised a structure of the linear generator with a dual translator power generation system. This structure has dual layered armatures to improve the amount of electricity generated. It would require extra external force to drive the generator but may be rather desirable in wave energy converter as it would enhance the performance of the damper. And the relative speed between the armature coils and HTS bulk field poles is increased by driving the dual translators. The improved design of the linear generator associated with the use of HTS bulk field poles increases the output power of the proposed linear generator. This is important innovation to improve the operational conditions that were difficult for the conventional generators to cope with: generating practical output power from general waves, which are characterized by low speed and high force.
It is necessary to develop a new design concept generator that operates at low speed with high torque or force ability to make ocean power generation a reality. By improving the speed of the linear generator, we show a new linear power generation structure that aims to improve the output power by adopting the dual translator power generation system, which increases the rate of change of magnetic flux through the armature copper coils. The use of HTS bulks increases the electromagnetic forces, which not only increases the output power of our proposed linear

generator but also improves its damping performance. We compared the results of our new conceptual linear generator structure with those of the simulation of the conventional linear generator structure. It was found that the proposed linear generator structure can increase electromagnetic force and power density higher than that of conventional linear generator structure. As expected, the combination of the dual translator power generation system and the HTS bulk field poles has the potential to help us to achieve higher torque, higher power density at a low ocean wave speed, which makes the proposed linear power generation structure suitable for our purpose. The proposed linear power generation structure is devised to meet the conditions required for ocean energy power generation, so it is expected to promote the practical application of ocean energy power generation systems.

Keywords: High-Temperature Superconducting Bulk, Ocean Energy, Wave Energy Converter, Linear Power Generator

AP2-4-INV

Status and Prospects for Superconducting Power Systems

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Superconducting Power Systems and several HTS-based devices have reached a high level of maturity (TRL). Presently, there are local and global trends challenging the existing systems and devices.

The worldwide Helium-shortage together with the reduced number of suppliers for superconducting wires and devices generates new opportunities for HTS-based devices.
The Energy Transition requires a reinforcement and modification of existing electric power grids.
The tough energy supply situation in Europe even tightens the challenges.
The pressure induced by the climate change to quickly move into the direction of more sustainable mobility is still increasing.

In this contribution we describe the needs of the German electric power grid and how HTS devices like Fault-Current-Limiters and Power-Transmission-Lines may contribute to a solution.
The opportunity of having vehicles using liquid hydrogen as a fuel -which might be a 'natural habitat for HTS'- opens up new prospects for HTS in propulsion systems of (large) vehicles.
We will report on some activities in selected German projects.

Keywords: SFCL, CABLE, MOTOR, HYDROGEN

AP3-1

Design and Build of a High-Speed AC Homopolar Superconducting Motor

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An AC Homopolar motor recently built at Robinson Research Institute demonstrates high operating speeds, wireless energisation of HTS coils, and a novel hybrid laminated steel stator. AC Homopolar motors magnetise a solid steel rotor using a non-rotating superconducting field coil rigidly mounted to the stator. As the field coils do not rotate with the rotor, cryogenic cooling and electric current can be supplied without rotating couplings. This architecture enables high speed operation, and large-scale AC Homopolar motors are expected to achieve over 12 kW/kg as required for aircraft powertrain applications.

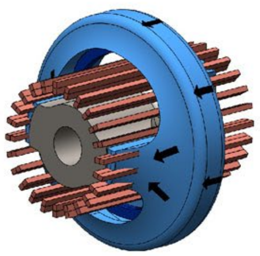
The 10 kW AC Homopolar motor built at Robinson Research Institute is designed for 30,000 RPM operation, 16,000 RPM faster than any previously demonstrated superconducting motor. This motor is designed as a modular testbed for superconducting technologies, and can be partially disassembled to facilitate modification or replacement of all superconducting components without the need for reengineering of the rotor.

Engineering work towards manufacture of this motor revealed the fully laminated stator described in previous work is not required, as much of the stator experiences non-alternating magnetic flux only. The built motor features a hybrid stator that includes low loss solid steel regions alongside conventional laminated steel stacks.

Current supply to the 200 A ReBCO field coil is supplied by a conventional DC source, but a variable speed HTS Dynamo is also included to demonstrate wireless energisation of closed superconducting circuits. The HTS Dynamo is designed to provide continuous and controllable superconducting circuit current without the large cryogenic load that results from current supply via copper leads.

In this presentation we will describe the operating principle of the AC Homopolar motor, including the revised understanding of the magnetic behaviour as developed through 3D finite element modelling techniques. We will also detail the manufactured motor design, including the unique features that enable this motor to be used as a testbed for a variety of superconducting motor technologies developed at Robinson Research Institute.

Keywords: Synchronous Motor, Hybrid Motor, Partial Superconducting Motor, Wireless Energisation



AP3-2

Thermal Characteristic Analysis of Fully Superconducting Motors Employing Dilute Gas Rotor Cooling Structure

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Electrification of aircraft propulsion systems is one of the key solutions for realizing Net Zero of CO_2 emission by 2050, given by ATAG (Air Transport Action Group). It is discussed that the installation of electric motors and power converters into the aircraft propulsion systems can be effective for the improvement of system efficiency. However, the weight of the electric equipment should be lighter than that of state-of-the-art motors and power converters. One of the demanded values is estimated over 16 kW/kg [1].

Superconducting technologies have a potential for achieving or excessing the upper values. The current density of the superconducting (SC) wires cooled at less than -200 ℃ for the rotating machines can be several ten or hundred times higher as much as copper windings. Also, stator iron teeth can be reduced thanks to high magnetic field generated by the SC windings; therefore, the weight of motors can be lighter than that of state-of-the-art motors.

There are two kinds of SC rotating machines such as partial SC motors (PSCMs) and fully SC motors (FSCMs). While the PSCMs have SC field windings and copper armature windings, both field and armature windings of the FSCMs are made of SC wires. The two SC windings of the FSCMs tend to put into the same cryostat and then the mechanical gap can be reduced in comparison with the PSCM structures; finally, power-density of the FSCMs can be higher than that of the PSCM structures, which have both SC and copper windings.

The authors have been studying the FSCMs using MgB_2 armature windings and REBCO field windings cooled at 20 K via liquid hydrogen [2]. The MgB_2 SC wires have multifilament structures, which have a potential to reduce AC losses. On the other hand, the REBCO wire have good Jc - B characteristics over 20 K. However, this FSCM structure demands two coolant paths for SC field/armature windings and results in complicated cooling structure. Therefore, the authors employed rotor cooling structures via dilute gas, while the stator side is still cooled at 20 K with liquid hydrogen. The REBCO field windings are operated below 50 K with heat conduction and convective heat transfer via dilute gas; this structure can simplify the rotor cooling structure. The authors conducted thermal and fluid analysis via finite element method to investigate the effect of the dilute gas cooling for SC field windings. By giving thermal load as electrical losses at the rotor part and changing parameters of pressure, rotation speed and so on, the cooling effect of this method is discussed.

References:

[1] B. Łukasik, "Turboelectric Distributed Propulsion System as a Future Replacement for Turbofan Engines," the ASME Turbo Expo 2017: Turbomachinery Technical Conference and Exposition GT2017, GT2017-63834, 2017.

[2] Y. Terao, Y. Ishida, H. Ohsaki and H. Oyori, "Electromagnetic Characteristic Comparison of Superconducting Synchronous Motor Characteristics for Electric Aircraft Propulsion Systems," SAE International Journal of Advances and Current Practices in Mobility, Vol. 2, pp. 828-837, 2019.

[3] M. Kato, Y. Terao, and H. Ohsaki, "Analytical and experimental study on the feasibility of rotor cooling with thin gas for fully superconducting rotating machines," Journal of Physics: Conference Series, Vol. 1857, No. 1, p. 012016, 2021.

Keywords: Electric aircraft, Dilute gas, Fully superconducting motors, Liquid hydrogen

AP3-3

Research on high-temperature superconducting induction/synchronous motor for transportation equipment with high power density

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In recent years, there has been a growing drive to develop high-temperature superconducting (HTS) rotating machines with high power density for power-based transportation applications, including aircraft, ship propulsion, and electric vehicles, where space and weight are at a premium.

However, when we designed the HTS electric machines, many parameters and coefficients of HTS electric machines were determined based on the empirical formulas and values accumulated by the predecessors.

A new approach called the self-organizing method was proposed to obtain optimized stator and rotor structures of HTS electric machines in a short time. The fully coupled electromagnetic models of a 30-kW class HTS synchronous/induction motor (HTS-ISM) with T-A formulation and H-formulation were developed to calculate the performance. The shielding current of the superconducting rotor bars in the HTS-ISM was clearly shown from the asynchronous to the synchronous state. Compared with the conventional design method, the new design method leads to an increase in power density and a decrease in torque ripple.

This work could be helpful for the quick design and analysis of future high-power density and high-efficiency HTS electric machines.

Keywords: Superconducting electric machine, Self-organizing method, Transportation applications

AP3-4

Superconducting motor for aircraft application using bulk material

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By 2050, the operational air fleet must have implemented an improvement of more than 90% in its carbon efficiency compared to the current fleet, in order to meet the objectives of halving the level of CO2 emissions in 2050 compared to those of 2005, while maintaining its projected growth rate. In this context, the members of the green working in the field of superconductor applications in electrical engineering are participating in the evolution of the aeronautical sector in this direction. Superconducting motors and generators are a potentially very interesting solution in the field of aeronautics. These superconducting devices allow to obtain very high powers and mass and volume torques. Moreover, the high efficiency of these machines makes them interesting in terms of energy saving. One of the goals is to find new superconducting machine structures or to optimize existing ones [1,2].

The static part of the inductor is composed of a superconducting coil producing an axial magnetizing field. The second element, a rotating part, is a set of superconducting bulk placed inside of the bore of the superconducting coil. These bulks shield the magnetic flux, and so flux density is then modulated between a low value near pellets and a high value elsewhere. The armature consists of a classical 3-phase windings made with copper without iron teeth in order to improve the performance.

One of the main problems is the ability of bulk superconductor to shield or trap magnetic field. Therefore, we present some element of design of a superconducting motor and the first tests on the bulks used in the rotating part.

[1] R. Dorget *et al.*, « Design of a 500 kW partially superconducting flux modulation machine for aircraft propulsion », *J. Phys. Conf. Ser.*, july 2021.
[2] R. Dorget *et al.*, « Review on the Use of Superconducting Bulks for Magnetic Screening in Electrical Machines for Aircraft Applications », *Materials*, jan. 2021.

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Keywords: Re-BCO Bulk, Superconducting Motor

AP4-1-INV

AC loss issues in all-superconducting rotating machines for aircraft applications

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Electric propulsion for aviation requires high power density and light weight all-superconducting motors and generators. However, superconductors in the armature windings of rotating machines carry AC currents under rotating magnetic fields and large AC loss generated in the armature windings poses a great challenge for the cooling system. Therefore, AC loss reduction in superconducting armature windings is one of critical tasks to underpin the application. Obvious conductor choices for the armature windings are REBCO coated conductors and multifilamentary MgB2 wires. However, YBCO wires may not be the best suitable choice due to their limitation in achievable filament size and difficulty in twisting the filaments. On the other hand, MgB_2 wires operating at 20 K are promising for the armature windings. The filament size can be as small as 10 mm which can result in considerable hysteresis loss reduction. Twist pitches have been demonstrated as low as 5 mm, and the copper can be moved, compared to DC MgB_2 wires. However, coupling loss in the normal conductors in the MgB_2 wires might be the dominant loss component for the application due to the high operating frequency. Therefore, one of urgent tasks is to accurately estimate the AC loss in the MgB_2 wires at actual operating conditions. There have been some analytical equations developed for AC loss estimations in MgB_2 wires. However, the analytical equations have not been validated by experimental results. Furthermore, the analytical equations have limitations for complex wire compositions and operational conditions. Therefore, we need experimental AC loss data in the MgB_2 wires operating under real operating conditions and simulation tools which are validated by experiment and can be extended to predict AC loss for more complicated wire structure and operating conditions which cannot be achieved by experiment.

In this work, we describe the measurement system under development at Robinson Research Institute, Victoria University of Wellington (VUW). The system when it is fully developed has a temperature range of 15 K – 80 K, magnetic fields up to 500 mT, and frequencies between 15 Hz – 200 Hz. The cooling will be enabled by circulating helium gas cooled by two powerful cryocoolers. The magnetic field will be generated by an air-core magnet wound with copper litz wires operating at liquid nitrogen temperature. AC loss in MgB_2 wires will be measured using the measurement system. In addition, we will experimentally evaluate AC loss in the MgB_2 wires at temperatures < 20 K by combining coupling loss and hysteresis loop measurement results. At VUW, we will carry out magnetization loop and critical current measurements on the MgB_2 wires to obtain hysteresis loss at operational temperatures and magnetic fields. At Kyoto University, using the state-of-the-art equipment, we will measure 4 K coupling loss in the MgB_2 wires in the

frequency range of 10 Hz – 10 kHz. The extrapolated AC loss results at 20 K in the MgB_2 wires will be compared with the measured results using the measurement system at VUW. Furthermore, AC loss in the MgB_2 wires under rotating magnetic field will be measured using the high dB/dt AC loss test rig at AFRL. The amplitude of the rotating magnetic field is 0.59 T and the temperature range of the measurement system is 10 K - 77 K when fully developed. The measured AC loss data in the MgB_2 wires at AFRL will be compared with the measured AC loss results using the other two measurement methods mentioned in the above. We will also present our 3D AC loss simulation in the multi-filament MgB_2 wires using COMSOL Multi-physics. Actual 3D filament shape and size, the resistivity in the sheaths and barrier will be considered in the simulation. Finally, we will compare AC loss in 3 MW all-superconducting motors using MgB_2 wires and striated REBCO conductors as a case-study.

Acknowledgment
This work was partly supported by the New Zealand Ministry of Business, Innovation and Employment under the Advanced Energy Technology Platform program "High power electric motors for large scale transport" contract number RTVU2004 and and partly supported by the Royal Society of New Zealand Catalyst: Seeding New Zealand – Japan Joint Research Project Programme contract number E4153.

Keywords: AC loss, MgB2 wires, REBCO conductors, All-superconducting rotating machines

AP4-2

DESIGN AND TEST OF A SET UP FOR CALORIMETRIC MEASUREMENTS OF AC TRANSPORT LOSSES OF HTS COILS

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This contribution presents the design and construction of a setup to measure transport AC losses in high-temperature superconducting coils based on a calorimetric approach. The evaporation of the cryogen (nitrogen) related to the dissipation of energy is collected by using a 3D printed bubble collector that guides the gas into a flow sensor. A box-inside-a-box approach is used to surround the measurement chamber with a cryogenic environment. This approach allows re-directing the heat transfer from the surroundings into an intermediate zone (space between external and internal box). Since this intermediate zone operates under cryogenic temperatures, the noise and the heat transfer in the internal part of the setup are reduced. The main signals (AC current, DC voltage of the power supply used for calibration and measured flow) are concentrated in a small circuit board and recorded by using an Arduino Uno and a Matlab App. This app shows the current values of the variables and a plot of the stored data.
Each measurement is done by considering a 60 minutes load cycle. During the first 30 minutes, the evaporation of cryogen related to the dissipated energy in the coil is measured. The background flow is measured in the next 30 minutes, when nitrogen re-fills can be done. Therefore, one can study the background flow behaviour during the whole measurement time and detect possible changes in the conditions of the environment that can influence the accuracy. The results are presented as average values and standard deviation, which allows studying the amount of variation and dispersion of the data and assess the uncertainty in the measurements. A well-known resistance is used to build a calibration curve that allows translating the flow of evaporated nitrogen into dissipation in Watts. In this contribution, we present the results of AC transport losses in a racetrack coil made with a 2 mm wide REBCO tape.

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Keywords: AC losses, Calorimetric measurements, Coil, High temperature superconductor

AP4-3

Electric field in coated conductors carrying ac current under ac external magnetic field

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For use in ac equipment such as rotating machines, the resistance of coated conductors cannot be regarded as zero, but coated conductors must be regarded as conductors with finite resistance that follows their non-linear *E–J* characteristics. In particular, at relatively high frequencies, electric fields much higher than the defining electric field E_0 of the critical current (generally 10^{-4} V/m) may be induced in the coated conductors. However, the formulation of the *E–J* characteristics of coated conductors used in numerical analyses is determined from measurements of the *V-I* characteristic of coated conductor in the electric field region of 10^{-5} V/m to 10^{-3} V/m generally. Namely, the electric field region governing electromagnetic phenomena in a coated conductor used for ac equipment may not match the electric field region targeted by the measurements used to determine the *E-J* characteristics in the analyses, which may affect the accuracy of the analyses. When evaluating the electromagnetic behavior of a coated conductor carrying an ac current under an ac magnetic field, it is not clear at what electric field region the *E-J* characteristics of the coated conductor are important.

We performed numerical electromagnetic field analyses of a single infinite-long coated conductor carrying an ac current under an ac magnetic field, and evaluated the electromagnetic field distribution inside the coated conductor to evaluate the electric field generated in the coated conductor under various ac environment. A single coated conductor with a width of 4 mm and a superconductor layer thickness of 2 mm was analyzed, and a power-law model was used for the *E-J* characteristics in the analyses. The critical current density J_c and defining electric field E_0 were set at 2.5 ´ 10^{10} A/m^2 and 1 ´ 10^{-4} V/m, respectively. Here, critical current of the coated conductor was 200 A, and J_c was assumed to be independent of the magnetic field for simplicity. The n-value was a parameter in the analyses and varied from 5 to 30. The amplitude of current was varied from 0 A to 150 A, and the amplitude of external magnetic field was varied from 0 T to 0.6 T. The frequency of current and magnetic field was from 20 Hz to 200 Hz, and the current and external magnetic field were in phase.

As a result, it was confirmed that the maximum electric field inside the coated conductor is almost independent of n-value while it is proportional to frequency. In the region where the external magnetic field can be considered sufficiently larger than the self-field due to the transport current, the maximum electric field is proportional to the amplitude of the external magnetic field. The magnitude of the electric field was found to be 0.1 V/m at an n-value of 30, a magnitude of current of 150 A, a magnitude of magnetic field of 0.6 T, and a frequency of 150 Hz, which is much higher than the defined electric field E_0. This suggests that the *E-J* characteristics in the high electric field region must be taken into account when performing electromagnetic field analyses of HTS coils or magnets wound with coated conductors for ac equipment.

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AP4-4

Numerical analysis of dynamic resistance and total loss in an HTS REBCO coated conductor carrying a DC current under a perpendicular AC magnetic field at various operating temperatures

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In some high-temperature superconductor (HTS) applications, such as field-triggered persistent current switches, flux pumps, and field windings of synchronous rotating machines, REBCO coated conductors (CC) carry DC currents under AC magnetic fields. The direct influence of the external AC magnetic field in these applications results in two types of AC losses: magnetisation loss due to the shielding current and dynamic loss due to the interaction between the AC field and DC transport current. The summation of these two loss components is referred to as the total loss. AC loss causes a parasitic heat load which has a significant impact on the sizing of the cryogenic system, whilst the operating temperatures for the applications could vary over a wide range and the amplitude of the external AC magnetic field could be large. As such, to successfully design systems, the behaviour of these losses under different conditions must be known. Current literature has focussed on experimental and simulation results of ReBCO CC for operating temperatures between 77 K – 65 K and magnetic fields up to 100 mT. However, there have been no reports for lower temperatures and magnetic flux density above 100 mT.

In this work, dynamic resistance and total loss in a 4 mm wide Superpower ReBCO CC are numerically investigated for various operating conditions using the 2D finite element modelling method based on the T-A formulation using COMSOL Multiphysics. Simulations are carried out for temperatures ranging from 30 K to 50 K under perpendicular magnetic fields up to 500 mT with differing values of the DC transport current. The dependence of the critical current of the REBCO CC on the magnitude of the applied magnetic field, field angle, and temperature is considered in order to understand the influence of the critical current on the dynamic resistance and total loss. The simulation results are then compared with the analytical values. Furthermore, the current density distribution and magnetic field penetration profiles are analysed to describe the relationship between the dynamic resistance and total loss and those parameters.

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This work was supported by the New Zealand Ministry of Business, Innovation and Employment under the Advanced Energy Technology Platform program “High power electric motors for large scale transport” contract number RTVU2004.

Keywords: HTS, Dynamic resistance, Total loss, AC loss

AP4-5

Experiments and numerical analyses of dynamic resistivities in copper-plated multifilament coated conductors

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Dynamic resistivities are generated in superconductors carrying dc currents under ac magnetic fields. Loss due to the dynamic resistivity (dynamic loss) is a type of hysteresis losses associated with the flux motion in superconductors. In coated conductors, multifilament structure, which divides the superconductor layer into multiple filaments in the width direction, is considered effective in reducing the dynamic loss and dynamic resistivity. However, in practical use, coated conductors are used with plated copper for improvement of stability, so that coupling currents are induced under ac magnetic fields, and the effect of multifilament structure can be obtained only when the time constant of the ac magnetic fields is sufficiently larger than the decay time constant of the coupling currents. To solve this problem, we have proposed a cable consisting of copper-plated multifilament coated conductors spirally wound around a cylindrical core, which we call spiral copper-plated striated coated-conductor (SCSC) cable (Figure 1).

We measured the dynamic resistivities and evaluated them by numerical electromagnetic field analyses to see if the reduction of the dynamic resistivities can be realized in SCSC cables. The dynamic resistivities in straight monofilament and multifilament coated conductors, and spiral monofilament and multifilament coated conductors are measured. We observed voltage evolution in the samples carrying dc transport current under ac magnetic fields and calculated dynamic losses from the measured voltage wave forms. Also, the same samples are numerically analyzed. As the results, the dynamic resistivity in straight copper-plated multifilament coated conductor was not reduced from it in straight monofilament coated conductor. However, it was confirmed that the dynamic resistivity was greatly reduced by making the copper-plated multifilament coated conductor spiral.

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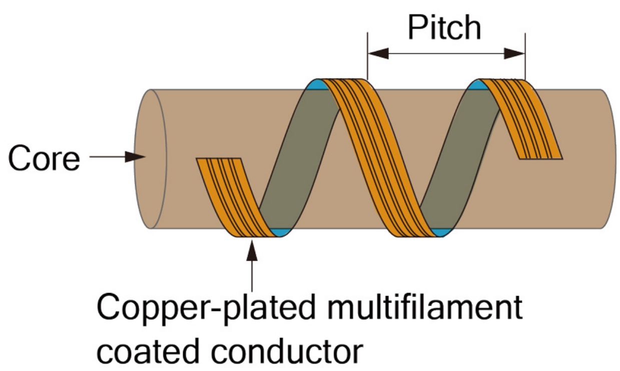
Keywords: Coated conductor, SCSC cable, Dynamic resistivity, AC loss



AP4-6

AC loss reduction methodologies for HTS coil windings coupled with an iron core

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As the second-generation synchrotron of therapy facilities for cancer treatment, rapid-cycling synchrotrons (RCSs) can meet the requirement of growing patient numbers. Supeferric magnets employing high temperature superconducting (HTS) coil windings and iron cores have potential to reduce the construction cost and electricity consumption for practical RCSs. However, AC loss generated in the HTS coil windings when carrying AC current increases significantly due to the presence of iron cores, making AC loss reduction a critical issue for HTS RCS application. Therefore, developing methodologies for AC loss reduction in the HTS coil windings coupled with iron cores is an urgent task for HTS RCS application.In this work, we carry out 3D FEM (Finite element method) AC loss simulations in HTS coil assemblies coupled with an iron core by using the T-A formulation. The HTS coil assemblies are comprised of double pancake coils (DPCs) wound with coated conductors manufactured by Shanghai Superconductor Co. with an average self-field Ic of 193 A. Flux diverters are positioned at the ends of the HTS windings to suppress the perpendicular magnetic field to the wide-face of coated conductors in the end part of the coil windings, and the distance between the iron core and coil assemblies is varied to investigate AC loss dependence on the distance. The simulated AC loss values in the HTS windings are compared.Acknowledgments:This work was supported in part by the New Zealand MBIE under Contract No. RTVU1707 and in part by the SSIF “Advanced Energy Technology Platforms” under Contract No. RTVU2004. Yue Wu acknowledges financial supports from the CSC and the CSC/Victoria University of Wellington Scholarship.

Keywords: AC loss, iron core, superconducting coils, 3D T-A homogenization method

AP5-1-INV

SUPERCONDUCTING ROTATING MACHINES

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Currently extensive development effort is being undertaken around world to develop compact lightweight motors possessing high efficiency for applications on airplanes and for the windfarm generators. This activity is being driven by carbon reduction goals set by many governments. Motors for airplane applications are being developed using a wide variety of technologies for meeting needs of selected aviation sectors. This talk discusses the benefits of superconducting machines and reviews machines built in the past, presently under construction and those planned. The future looks bright for the machines employing high temperature superconductors.

AP5-2-INV

Electromagnetic Analysis of Fully Superconducting Motors Employing Dilute Gas Rotor Cooling and Liquid Hydrogen Stator Cooling Structure

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Aviation industry has accelerated effort to reduce greenhouse gas emission based on the statement of ATAG (Air Transport Action Group); Targeting Net Zero of CO_2 emission by 2050. One of the solutions to achieve this statement is electrification of aircraft propulsion systems.

Fully superconducting rotating machines (FSCMs) are one of the most effective solutions for realizing high-power density machines applicable to electric aircraft propulsion systems. This is because, superconducting field/armature windings have high current density at ultra-low temperature and can generate higher magnetic field. Therefore, weight of windings and iron can be reduced and then, light weight motor/generators are available. So, the authors have been proposing the FSCMs using two kinds of superconducting windings; MgB_2 armature windings and REBCO field windings [1, 2].

However, the cooling structures for the FSCMs tend to be complicated because both armature and field windings demand coolant, refrigerators and so on.

In such a technical challenge, the authors employed cooling method using dilute gas as well as liquid hydrogen [3]. While the MgB_2 armature windings are cooled at 20 K via liquid hydrogen, the REBCO field windings are operated below 50 K with heat conduction and convective heat transfer via dilute gas. This structure contributes to simplifying the rotor cooling structure.

In this study, the authors conducted electromagnetic design of the FSCMs via finite element method (FEM) with considering not only active material parts but also important structural parts. And based on these analysis results, motor output density, losses, and so on are evaluated and discussed.

References:

[1] Y. Terao, W. Kong, H. Ohsaki, H. Oyori and N. Morioka “Electromagnetic Design of Superconducting Synchronous Motors for Electric Aircraft Propulsion,” IEEE Transactions on Applied Superconductivity, *Vol. 28*, no. 4, pp. 1-5 (2018).

[2] Y. Terao, Y. Ishida, H. Ohsaki and H. Oyori, “Electromagnetic Characteristic Comparison of Superconducting Synchronous Motor Characteristics for Electric Aircraft Propulsion Systems,” SAE International Journal of Advances and Current Practices in Mobility, Vol. 2, pp. 828-837, (2019).

[3] M. Kato, Y. Terao, and H. Ohsaki, "Analytical and experimental study on the feasibility of rotor cooling with thin gas for fully superconducting rotating machines," Journal of Physics: Conference Series, Vol. 1857, No. 1, p. 012016, 2021.

Keywords: Dilute gas, Electric aircraft, Fully superconducting motors, Liquid hydrogen

AP5-3

Development of 40-MW-class Electric-Wire-Interconnect-System (EWIS) for Electric Aircraft

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The development of electric aircraft is evolving rapidly worldwide, with over 600 aircraft being developed as of July 2022. And pre-sales have been announced publicly exceeding 5,500 aircraft and $30B, for aircraft not even built or certified yet. With this fast evolution, there is increasing understanding that currently available commercial-off-the-shelf (COTS) drivetrain technologies are far too heavy and inefficient especially for > 10 passenger aircraft, and there is need to develop new drivetrain technologies with ~ 10x lower weight and heat loss. It is increasingly understood that superconductivity/cryogenic technologies have the potential to meet those needed goals.

In this presentation, the development of a 40-MW-class electric-wire-interconnect system (EWIS) will be presented for electric propulsion, e.g., powered by liquid H_2 fuel-cell propulsion plus Li-batteries or other hybrid-electric options. The study will compare using known electric wire options including Al-based wire at ambient temperatures, Al 99.999% 'hyperconductor' @ 20K, and Cu-oxide or MgB_2 coated conductors @ 20-77K. The design trades and options to optimize the weight and efficiency will be considered. And the mass and heat loss scaling laws of the drivetrain components are required for varying power/voltage /ampacity levels (0-20 kA) and power-wire distribution architectures, which is a focus of this work. Drivetrain components studied thus far include cable designs, bus bars, current leads, metal/superconducting Tee-joints, cryoflex tubing and cooling system, high voltage insulation, breakers, switches and FCL's.
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Keywords: electric aircraft, electric wire interconnect system, power distribution system, cryogenics, superconductivity

AP5-4

Demonstration of rotation characteristics during transition between the boiling point of liquid nitrogen and room temperature in a 6 kW-class high temperature superconducting induction/synchronous motor

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Our research group has researched and developed a High Temperature Superconducting Induction/Synchronous Motor (HTS-ISM) as a high efficiency and high torque density motor. The HTS-ISM can realize high-performance rotating characteristics that cannot be achieved with conventional (normal-conducting) motors by effectively utilizing the zero resistance and nonlinear current transport characteristics of the HTS conductors [1]. However, a major problem with the HTS motors is the need to cool them to cryogenic temperature, and the event of having to stop the rotation system when the cooling system fails is not practical. In order to overcome the above problems, a group of Kyoto University proposed a normal conductor/superconductor hybrid squirrel-cage winding and showed the possibility of continuous drive near the superconducting critical temperature [2]. By using this winding, when the HTS conductor is in a superconducting state, a superconducting current is induced in the conductor, realizing high performance rotation. On the other hand, if the conductor transitions to the normal conducting state, the current will automatically transfer to the normal conductor, reducing the output and allowing the rotation to continue. Based on the preliminary results, the analytical study on the continuous drive of the HTS-ISM from room temperature to the cryogenic temperature is carried out [3].

In this study, a prototype HTS-ISM with a maximum synchronous output of 6 kW at a temperature of 77 K (atmospheric boiling point of nitrogen) and a rated slip output of 1.5 kW at room temperature was fabricated. The motor consists of a copper wound stator and a superconducting BSCCO/copper hybrid cage rotor. As a result of the rotation test, not only the synchronous rotation at the temperature of 77 K but also the continuous slip rotation test at room temperature were succeeded. At the presentation, detailed test results such as current waveforms and transition drive tests between the superconducting state and the normal conducting state will be reported.

[1] G. Morita, T. Nakamura and I. Muta, Supercond. Sci. Technol., 19(6) (2006) 473
[2] T. Nakamura et al., Supercond. Sci. Technol., 22(4) (2009) 045022
[3] T. Nakamura et al., TEION KOGAKU (J. Cryo. Soc. Jpn.), 51(5) (2016) 178 (in Japanese)

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Keywords: Fault tolerance, HTS-ISM, Non-superconducting rotation, Super-&normal-conductors hybrid cage

AP6-1-INV

Recent Advances in Ultra-High Field Superconducting Magnets - 2022

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If we define ultra-high field (UHF) magnets as those that provide fields more intense than the 23.4 T available from low temperature superconductors, then we see tremendous progress being made worldwide in recent years. An absolute revolution is underway in superconducting magnets with the high temperature superconductors (HTS) finally finding their way into condensed matter (Sendai 25 T, Tallahassee 32 T) and NMR (Bruker 28.2 T) magnets in routine operation. Newer applications such as axion detection are also being enabled by this revolution (Daejeon 25 T, 10 cm). Projects are underway for a number of 30 T-class condensed matter magnets around the world as well as a few organizations pursuing 30.5 T NMR and 40 T for condensed matter.

A number of technologies are being pursued. A Bi-2223 coil has been put into service at 25 T while insulated REBCO has served users at 32 T. A test coil using no-insulation REBCO made 14 T in a 31 T background (45 T total) while dramatic improvements in Bi-2212 show great potential as well. The record field from a superconducting magnet rose from 23.5 T to 24 T to 32 T in less than one year. The previous 8 T increase required >40 years! The technology is evolving at an unprecedented rate! At the same time, costs show great promise of dropping which may enable this extraordinary technology to become fairly widespread.

HTS magnet technology is also creating a new commercial industry: magnetic confinement for fusion. This field has been dominated by national governments for decades, but the HTS materials allow more compact designs at higher field to be developed which show potential to reduce the cost of a tokamak. While these magnets are not "UHF" large-scale financing is being organized and technical improvements in this community is impacting the UHF community. While differetn groups and applications use different UHF magnet technologies, they all still share central challenges such as how to manage intense Lorentz forces as well as the required energy and power. The state of the art and challenges associated with further development of a variety of ultra-high field magnet systems is presented.

Keywords: High field magnet, 2G HTS magnet, large-scale superconducting system

AP6-2-INV

High-field high-temperature superconducting accelerator magnets at the Berkeley lab

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This talk gives an overview of the design, fabrication, and test efforts of the development of high-field high-temperature superconducting accelerator magnets in the USA with a focus on efforts of developing the canted-cosine-theta Bi-2212 and REBCO magnets at the Berkeley lab. Several prototype magnets have been built and tested in the standalone configurations and we are planning to test them in a background magnets field provided by Nb_3Sn magnets. Several engineering challenges will be discussed, in particularly the issue of dealing with the effects of electromagnetic coupling and electromechanical interactions between insert and outsert magnets on electrical and mechanical safety and quench protection. Moreover, quench detection of two Bi-2212 standalone accelerator magnets (common coil configuration and canted-cosine-theta) built and tested will be compared and analyzed to shed lights on questions such as what is the limit of the voltage tap based quench detection, and how can it be improved relative to the dogma established for Nb-Ti and Nb_3Sn accelerator magnets. A third topic is the fundamental concept of the margin of safety of the HTS magnets. A revised MIITS (I^2t) method that suits for HTS magnets than the prevalent method for Nb-Ti and Nb_3Sn magnets will be introduced for analyzing the hot spot temperature, and illustrate how can the margin of safety be improved with improved quench detection and for the case of the common coil configuration Bi-2212 accelerator magnets by a significant degree.

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Keywords: High temperature superconducting magnets, Superconducting accelerator magnets, Quench protection

AP6-3-INV

Development of Exciter System for Power Supply Driven HTS-MRI

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The development of helium free high-temperature superconducting (HTS)-MRI magnet is expected. An HTS-MRI magnet made of HTC tape superconductors has difficulties in the persistent current exciting mode for producing a highly stabilized magnetic field for MRI imaging, due to a screening current in REBCO tape. Furthermore, development is necessary in non-resistive joint and persistent current switch of REBCO MRI magnet.

One solution for these problems is an active magnetic field stability control by use of a power supply instead of the persistent current operation. We have developed the power supply system consists of a exciter power supply and a small trimming current supply which compensates the magnetic field deviation due to the screening current. The MRI magnetic field feedback/feedforward control test was carried out, that is, the overshooting and the current trimming control, using a HTS-MRI test magnet.

In this paper, we measured and evaluated the magnetic field stability, using a HTS-MRI test magnet in the power supply driving mode using a dropper-type and of a switching-type direct-current exciter system. A high stable direct current power supply is normally designed using the dropper-type regulator which is suitable for the constant current operation of less current ripple. However, it is of large power loss and is not suitable for charging/discharging operation. On the other hand, the switching-type regulator is suitable for the variable current control operation and of less power loss. However, it is of large current ripple in the constant current operation which would degrades the magnetic field stability in HTS-MRI imaging operation.

The HTS-MRI magnet which is fabricated by REBCO tape superconductor was charged up to 20.5A with ramp rate of 0.05 A/s and then discharged to target current 20A (0.27 T), that is the overshoot charging operation for compensating the screening current effect on the magnetic field stability. The magnet current was kept 20 A for about 3 hours. The magnet field stability at the center of imaging area, the magnet current and the magnet terminal voltage were examined. In case of the dropper-type exciter, the terminal voltage instability was observed in the charging operation, and the magnetic field stability was evaluated as 3.70 ppm/h in 3 hours of the constant current mode. In case of the switching-type exciter, the magnet current was smoothly built up without any voltage instability, and the magnetic field stability was evaluated as 6.69 ppm/h in 3 hours of the constant current mode but the voltage ripple was observed.

The availability of the power supply system was discussed in MRI imaging of a mouse using an experimental HTS-MRI system. The MRI image of the mouse was obtained under the power supply driven operation of the dropper-type regulator. The S/N ratio of the image was 6~7 in the imaging time of 15 minutes and 19 of 120 minutes which is similar level to that of the commercial LTS-MRI system with persistent current mode. On the other hand, the clear MRI image of the mouse was not obtained under the power supply driven operation of the switching-type regulator due to the small but repetitive fluctuation in the magnetic field due to the voltage ripple.

A resistor of 1.2 ohm was set between the magnet terminal in parallel to the MRI magnet in order to improve the magnetic field stability in the constant current mode for the clear MRI imaging, at the same time to alleviate the current instability in the charging mode with the dropper-type power supply and to reduce the magnet current ripple due to the voltage ripple in the constant current mode with the switching-type one. As a result, the magnet current was smoothly built up and the magnetic field stability was improved to 1.98 ppm/h with the dropper-type power supply. The voltage ripple was still observed in the constant current mode but the magnetic stability was improved to 5.53 ppm/h with the switching-type power supply. The MRI image of the mouse was obtained under the power supply driven operation of the switching-type regulator, since the magnetic field ripple due to the voltage ripple was reduced by the parallel resistor. The S/N ratio of the image was almost the same (19) as with the dropper-type one in the imaging time of 120 minutes. The power loss of the switching-type power supply is about 1/6 of that of the dropper-type one.

This work was supported by NEDO "development of an HTS magnet system with highly stable magnetic field" as part of the "promotion technology development for HTS practical application."

Keywords: High Temperature Superconductor, MRI magnet, Exciter system, magnetic field

AP7-1-INV

Development of Ultra-Baby HTS magnet for Skeleton Cyclotron Accelerator

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We have been developing an air-core cyclotron accelerator, named “Skeleton Cyclotron Accelerator,” for the purpose of a next-generation medical application. Mass production of short-lived alpha-emitting nuclei such as At-211 and Ac-225 is desired for a targeted α-particle cancer therapy (TAT). A compact, light-weighted, and high intensity accelerator is required to be developed, since it is installed in a hospital. Due to air-core, the skeleton cyclotron accelerator has a unique character of variable energy and multiparticle acceleration to produce radioisotope (RI) for PET, TAT and other theranostics applications. We have previously investigated a magnetic field necessary for the cyclotron, that is composed by an isochronous and azimuthally varying field, and developed a design method of high field coils wound with Rare-Earth Barium Copper Oxide (REBCO) coated conductors.

We have also developed the 5-H (High thermal stability, High current density, High mechanical strength, High field & compactness, and Highly precise field) technology to maximize the REBCO characteristics. In the 5-H project, we have investigated the YORI reinforcement which can protect REBCO coils from a high electromagnetic force by surrounding the coils with stainless steel cases. The screening current induced fields were numerically investigated the effect on the beam trajectory.

To confirm the validity of the developed technologies, we designed a miniaturized REBCO magnet, called “ultra-baby” skeleton cyclotron HTS magnet. In addition, the stress/strain of a non-circular (triangle) coil which was a sector coil to generate the azimuthally varying field was previously measured in experiments. As the next step, we are now manufacturing “ultra-baby” cyclotron HTS magnet system. In this fall, we will measure the magnetic field map on the mid-plane where particles are accelerated. In our presentation, the field accuracy and the stress/strain profiles are shown as a progress of the development of skeleton cyclotron accelerator.

Keywords: HTS magnet, Cyclotron Accelerator

AP7-2-INV

Application of superconducting flux pumps to MRI magnet systems

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There is a very real need for compact MRI's which are small and light enough to be essentially portable. This is especially true when you consider strokes. Rapid diagnosis enables fast treatment and is essential before commencing treatment to determine the type of stroke.

As such there is a clear need for a compact MRI. Using HTS provides the means to achieve this by supporting a very high current density. Thus, we can reduce the size, weight and inductance of the MRI magnet. We can further reduce the mass of the magnet by using a flux pump as the power source. As a result the magnet can be rapidly deployed and brought to the patient rather than the other way around opening up the possibility that ambulances can be equipped with MRI machines. This would revolutionise stroke diagnosis and treatment, saving lives and minimising clinical effects damage and recovery times.

We have built a magnet which is designed to run at 500 Amps and will provide a 1T imaging field. The magnet has an inductance of 85 mH and uses 3km of tape. The internal diameter of the magnet is 55cm which is sufficient to fit the shoulders of an adult male. The magnet has been designed in Cambridge, built in China by Professor Liu's team and assembled in Cambridge. We will present data from the magnet re the overall uniformity of the field, the stability of the field and the overall mass of the system.

Keywords: MRI, Flux Pumps, Cephalic Imaging, HTS

AP8-1-INV

HTS fusion magnet

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On route to developing zero carbon emission commercial electrical power generation, Tokamak Energy (TE) is developing Spherical Tokamak (ST) technology. A key enabling technology for ST machines is the development of HTS magnets. TE has embarked on a program of developing HTS magnets based on REBCO coated conductors for ST's up to fusion reactor scale magnet sets. This presentation will summarise the challenges and the progress of that program to date.

AP8-2

Numerical Analysis of a Hybrid REBaCuO-Cu Coating for the FCC Beam Screen: Misalignments, Creep and Harmonic Correction

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CERN's Future Circular Collider (FCC) is the most ambitious scenario for a next generation particle accelerator. With 16T magnetic fields in a 100 km acceleration ring, center-of-mass collision energies of 100 TeV will be reached. To shield the steering superconducting magnets from the 35.4 W/m/beam synchrotron radiation emitted by the particle beam, a highly conductive metallic structure, the beam screen, surrounds the particle trajectory, absorbing the radiation, at a temperature window of 40 – 60 K. During operation, image currents will be induced in the beam screen, risking beam stability. To minimize this destabilizing effect, our consortium studies a hybrid coating for the beam screen, made of CU and REBaCuO (RE = rare earth) Coated Conductors (CCs). This combination ensures not only a low surface impedance, but also meets the field homogeneity criterion of a few units over 10000 imposed by CERN, which is necessary to preserve proper particle trajectory. In this work, we use the finite elements method and H-formulation to explore the field quality of the hybrid coating when submitted to the dipole and quadrupole fields that will be applied to the beam screen. Since the angle of the magnetic field with regards to the superconductor will be different along its width, particularly for the quadrupole field, our model accounts for the anisotropy of the superconductor, as well as creep effects and the field dependence of the superconducting properties. We analyze how field harmonics are affected by displacing and tilting the beam screen with regards to the external field and how they change over time during beam injection. Finally, we discuss the possibility of using the hybrid coating with the correction circuits of the dipole magnets to achieve a combined effect to partially cancel some of the field harmonics, increasing field homogeneity.

Keywords: Future Circular Collider, REBCO, Field Quality, Beam Screen Coating

AP8-3

Coupled electro-magnetic and electro-thermal model for non-insulated and metal-insulated high field magnets

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Non-insulated (NI) and metal-insulated (MI) coils in superconducting REBCO high-field magnets provide electro-thermal stability. However, current transfer between turns through the metal causes transient currents and magnetic fields, increasing the AC loss and requiring longer times to charge the magnet. Therefore, magnet design and optimization needs numerical modeling. Although 3D modeling provides the full description, it is highly time consuming. In this contribution, we propose an effective cross-sectional 2D modeling method to model the screening currents and turn-to-turn currents in non-insulated coils within high-field magnets. This technique is based on the Minimum Electro-Magnetic Entropy Production method (MEMEP) [1,2], which is programmed in C++ and enables parallel computing [2,3]. First, we benchmark this method with a different method based on the A-phi formulation [4] coded in Matlab language. By means of MEMEP, we analyze the screening currents, instantaneous AC loss and generated magnetic field in tentative designs of high-field superconducting magnets generating more than 32 T. In addition, we developped a finite difference method, programmed in C++, to model the electro-thermal quench properties of the windings. The model developed can be used for a quick and complete electro-magnetic and electro-thermal analysis of practical superconducting applications, specially for high field magnets.

[1] E Pardo, J Souc, L Frolek, Electromagnetic modelling of superconductors with a smooth current–voltage relation: variational principle and coils from a few turns to large magnets, Supercond. Sci. Technol. 28, 044003 (2015)
[2] E Pardo, M Kapolka, 3D computation of non-linear eddy currents: Variational method and superconducting cubic bulk, J. Comp. Phys. 344, 339-363 (2017)
[3] E Pardo, Modeling of screening currents in coated conductor magnets containing up to 40000 turns, Supercond. Sci. Technol. 29, 085004 (2016)
[4] P Fazilleau and G Dilasser, Vortex shaking study with use of linear voltage-current law, Supercond. Sci. Technol. 35, 045007 (2022).

Keywords: High magnetic field magnets, Non-insulated coils, Screening current modelling, Electro-thermal quench modelling

AP9-1-INV

Magnetic Refrigeration for Cryogen Liquefaction

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ABSTRACT — One of the major global challenges we are embracing is supply of sustainable, economical, and environmentally friendly fuels for transportation uses. Several unique properties of hydrogen make it an attractive candidate, especially given importance of reducing impact of high-carbon fuels on climate change. Although hydrogen has very high gravimetric energy density, it has very low volumetric energy density. For cost-effective storage, transport, distribution and use on-board heavy-duty fuel-cell electric vehicles, marine vessels, railway engines, and avionic applications, liquid hydrogen (LH_2) is required. Efficient, distributed scale magnetocaloric liquefiers are under development to fill a need for safe, reliable, economic, and expanding LH_2 refueling infrastructure. Cost-effective active magnetic regenerative liquefiers (AMRLs) require optimal integration of about eight subsystems into modular units to achieve high thermodynamic efficiency at 1-10 metric tons/day capacity. Most of the development have focused on three critical subsystems; magnetic refrigerants in magnetic regenerator(s), liquid, and gas heat transfer fluid flow(s); and superconducting magnets with regions of constant magnetic flux densities of 6-7 tesla. This talk will describe some recent advances in AMRLs for LH_2 with emphasis on the superconducting magnet subsystem. Trade-offs between use of Nb_3Sn at 4 K vs. ReBCO at 20 K will be briefly discussed.

Keywords: Magnetic, Refrigeration, Liquefaction, LH2

AP9-2

Removal of martensitic transformation SUS304 fine particles by a high gradient magnetic separation under dry condition

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The interfusion of impurities such as metallic wear debris has been one of the problems in the manufacturing process of foods, medicines, and industrial products. Such debris originates with wearing of stainless-steel pipe joints or mechanical moving parts. Since the debris shows the ferromagnetic property by undergoing strain-induced martensitic transformation, the magnetic separation system is much efficient to remove such debris from raw materials. In order to study magnetic separation properties for martensitic transformed materials as foreign matter, we have produced martensitic transformed materials with different magnetization by heat-treating SUS304 power at various temperatures in vacuum, and conducted magnetic separation experiments using a multilayer magnetic filter under dry condition. The magnetic separation experiments and 3D FEM particle trajectory simulation show that martensitic transformation SUS304 fine particles were possible to be collected at high speed of more than 0.1 m/s by a high gradient superconducting magnetic filter even in low magnetic fields under 1 T.

Keywords: HGMS, stainless-steel, martensitic transformation, magnetic filter

AP9-3

Fundamental study of the removal of microplastic fibers using swirling flow and magnetic field

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1. Introduction

The impact of microplastics leaking into the environment on the ecosystems is one of the serious issues. One type is microplastic fibers (MPFs), which are contained in laundry wastewater. There is concern that MPFs may pass through sewage treatment facilities and affect the ecosystem by adsorbing toxic substances and their uptake by living organisms.

We have been investigating a method of magnetite adhesion to the surface of MPFs and removal by magnetic force by applying a magnetic field. However, in normal high-gradient magnetic separation systems (HGMS), the magnetic force acting on magnetite exceeds the adhesion force between MPFs and magnetite, causing the magnetite to desorb from the MPFs. To solve the problem, we evaluated the possibility of magnetic separation of MPFs by a magnetic separation system using a swirling flow and magnetic field.

2. Analysis Method

As shown in Figure 1, a flow channel model was created to generate a swirling flow inside a circular tube. This model consists of a circular tube with a radius of 45 mm and a height of 200 mm, with an inlet on the upper side of the tube and outlets on the lower side (Outlet 1) and the center of the tube (Outlet 2). Although the use of opposed superconducting magnets is considered for practical use, for basic study, quadrupole opposed magnets with a maximum flux density of 0.4 T were installed so that the direction of the magnetic force acting on the MPFs is in the radial direction of the circular tube. The velocity and magnetic field distributions in the circular channel were analyzed using finite element method analysis software (Ansys 2021R1, Cybernet Systems Co., Ltd.). Based on microscopic observations of beaker-scale magnetic separation experiments using polyester as MPFs, we assumed that 1,700 magnetite particles (0.5 μm in diameter) adhere to one MPFs of 400 μm in length and 10 μm in diameter. The motion equations for the particles considering magnetic and drag forces are solved in time evolution using the fourth-order Runge-Kutta method to analyze the position of the particles on the cross-section of the circular tube at the center of the magnetic field region.

3. Results and Discussion

The trajectory of magnetite-adhered MPFs on the cross-section of the circular tube at the center of the magnetic field region is shown in Figure 2. Comparing the trajectory of the MPFs with and without the magnet, it was found that the MPFs were directed toward the wall due to magnetic forces. This is because the magnetic flux density in the channel is almost 0 T around the center whereas 0.4 T at the wall, resulting in magnetic forces acting on the MPFs in the wall direction. MPFs flowing into the channel gather in the direction of the wall due to the swirling flow but are further efficiently pulled in the direction of the wall by the assisting magnetic force. Thus, it is expected to cause a high concentration of MPFs simulated wastewater to flow out of Outlet 1 at the side and a low concentration to flow out of Outlet 2 at the center. In addition, the use of superconducting magnets allows the application of a magnetic field over a wide area, making it possible to increase the radius of the circular tube, which would enable the high-speed mass processing of wastewater.

4. Conclusion

Simulated wastewater containing magnetite-adhered MPFs flowed into a channel that generates a swirling flow, and the trajectory of the MPFs was analyzed when a magnetic field was applied by a quadrupole opposed magnet and without a magnetic field. The results show that it is possible to achieve high concentrations of MPFs by applying a magnetic field near the wall surface, compared to the case of only swirling flow. Based on these results, it is expected that high-efficient MPFs removal can be achieved by a magnetic separation system assisted by a swirling flow and magnetic field. For practical use, we plan to conduct further simulations and experiments to clarify the conditions necessary for the efficient removal of MPFs.

Keywords: microplastic fibers, swirling flow, magnetic force, magnetite

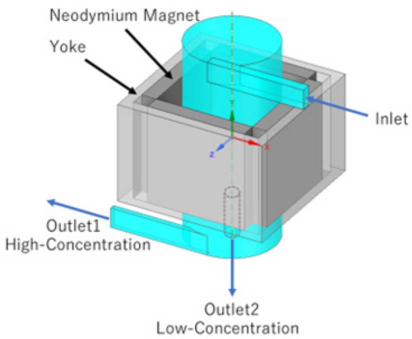

Figure 1 Schematic diagram of a magnetic separation system

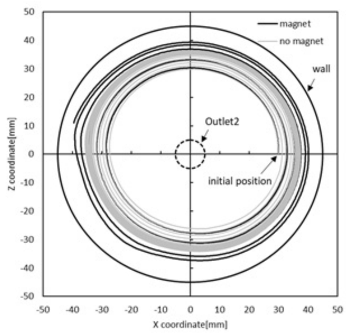

Figure 2 The trajectory of magnetite-adhered MPFs on the cross-section of the circular tube

AP9-4

All-optical non-contact level sensor for liquid hydrogen

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The transition to renewable energy will require us to deal with intermittent energy sources such as solar and wind at scale [1]. To balance the supply and demand, we need either to expand the ability of large-distance energy transmission over the power grid [2], or to develop a large-scale, cost-efficient energy storage [3], or both. Liquid hydrogen could play significant roles in these cases, as coolant for superconducting cables [4] or as chemical energy storage. Hence accurate, convenient, and safe liquid level sensors could be a significant support technology in the era of renewable energy.

Liquid hydrogen level sensors based on a variety of physical principles have been developed and, in many cases, commercialized. Existing sensors include the differential pressure level gauge [5], capacitive liquid level sensor [6], and the MgB_2-based superconducting liquid level sensor [7]. In all these cases, however, either physical components or electrical wires, or both, are immersed in the liquid hydrogen. In particular, the electrical wirings are associated with a risk, or a perceived risk by the user, of potentially explosive failure when, e.g., lightning strikes a nearby point or the equipment itself.

In the present work, we intend to develop an all-optical liquid level sensor. The sensor monitors the liquid level from a physically remote position, i.e. at the top of the tank. The principle is simple: We illuminate the liquid surface by multiple light sources and simply observe the reflected image with a camera. In the present case, we illuminate the surface with three optical point sources and hence the reflected image is an equilateral triangle comprising three bright spots. We then infer the position of the liquid surface from the size of the reflected image. Illumination of the liquid surface is accomplished with a laser and a few optical fibers, while the image of the reflected light is transferred through an optical fiber bundle. Thus, the above-mentioned potential risk from electrical wiring is eliminated because we do not connect any electrical wirings to the sensor body. Moreover, the lack of direct contact to the liquid mass means that we avoid loss of the liquid due to heat conduction along the sensor body.

On the other hand, we emphasize that we are still at the initial phase of development and we foresee several potential challenges. Firstly, decent measurement precision of the liquid level would require high precision measurement of angles, with which reflected light rays come to the sensor. The needed angular precision is given as follows. Let the side length of the illuminating triangle, i.e., the separation between the tips of the illuminating optical fibers, be d. In the present case d = 26 mm. Also, let the distance between the sensor and the liquid surface be L. The angle to be measured is of the order of $\theta \approx d/L$, and hence the change of angle $\delta\theta$ resulting from the change of the liquid level δL is $\delta\theta \approx d\delta L/L^2$. Secondly, we would need certain averaging of the images when the liquid surface is not still. In view of the cheap computing power that we have today, we are optimistic that video image processing would cost virtually nothing.

Figure 1 shows our preliminary test results using liquid nitrogen instead of liquid hydrogen. Figure 1 (a) shows the entire measurement setup. Figure 1 (b) shows the sensor head, wherein few of the three illuminating fibers, a lens, and the rigid fiber bundle for imaging are visible. Figures 1 (c) and (d) show images of reflected light spots appearing on the other end of the imaging fiber bundle. The distance between the sensor and the liquid surface is approximately 12 cm and 21 cm for Figs. 1 (c) and (d), respectively.

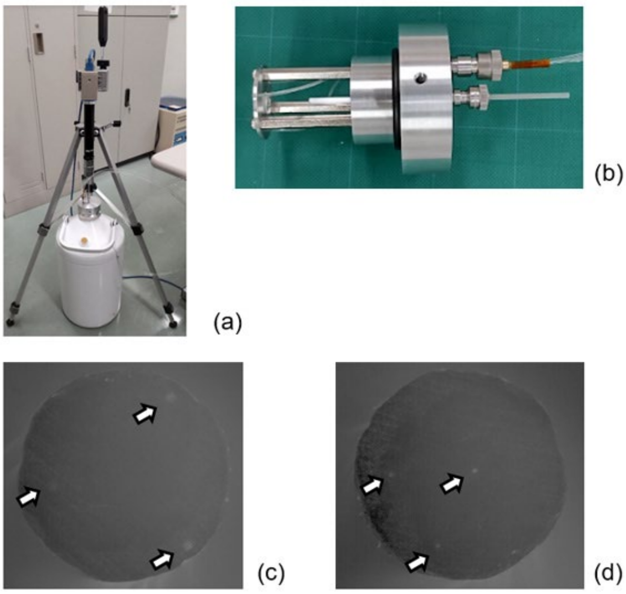
We thank Professor Teruo Bitoh for his assistance in developing the experimental setup. We also thank Professors Shin-ya Matsushita and Hiroto Kawashima for discussions and for providing us with liquid nitrogen, respectively. This research was supported in part by the grant donated by Eurus Energy Akita-Port Corporation to Akita Prefectural University.

FIG. 1. (a) All-optical non-contact liquid level sensor setup. (b) The sensor body. The pitch of the grid in the background is 50 mm. (c), (d): Images corresponding to two different liquid levels appearing on the end of the ϕ3.2 mm-diameter fiber bundle. See the main text for more information.

References

[1] Anne Sjoerd Brouwer, Machteld van den Broek, Ad Seebregts, and Andre Faaij, Impacts of large-scale Intermittent Renewable Energy Sources on electricity systems, and how these can be modeled, Renew. Sust. Energ. Rev. 33, 443-466 (2014).
[2] Mircea Ardelean and Philip Minnebo, HVDC Submarine Power Cables in the World, Joint Research Centre, European Union, Report EUR 27527 EN (2015).
[3] Paul Breeze, Hydrogen Energy Storage, Chapter 8, Power System Energy Storage Technologies, Pages 69-77, Academic Press (2018).
[4] Paul M. Grant, Chauncey Starr, and Thomas J. Overbye, A Power Grid for the Hydrogen Economy. Scientific American (June 2006).
[5] W. A. Olsen, A Survey of Mass and Level Gauging Techniques for Liquid Hydrogen. In: K.D. Timmerhaus (eds), Advances in Cryogenic Engineering, vol 8. Springer, Boston, MA. (1963).
[6] Koichi Matsumoto, Masamitsu Sobue, Kai Asamoto, Yuta Nishimura, Satoshi Abe, and Takenori Numazawa, Capacitive level sensor for liquid hydrogen, Cryogenics 51, 114-115 (2011).
[7] Ch. Haberstroh and G. Zick, A Superconductive MgB2 Level Sensor for Liquid Hydrogen, AIP Conference Proceedings 823, 679 (2006).

Keywords: Superconducting Power Transmission, Refrigerant Storage, Liquid Hydrogen, All-optical Non-contact Level Sensor



AP9-6

Detection of localized hot spots at 80 K using distributed fibre Bragg gratings

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The incredible current density and high magnetic field generation possible with high-temperature superconductors (HTS) have the potential to revolutionize energy generation, e.g. high-power generators, and compact fusion energy devices. However, the challenge of rapidly detecting a localized hot spot in HTS before a quench is even developed, remains unsolved. Our group previously demonstrated the functionality of an ultra-long fibre Bragg grating (ULFBG), an array of FBGs with the same Bragg wavelength, in detecting a hot spot in a HTS tape. In this talk, a 10 m ULFBG is shown to behave like a 'distributed' sensor, which can detect 30 mm localized hot spots along its length at 80 K within a 5 K temperature rise. ULFBG can significantly improve the limitations of spatial resolution of discrete FBGs in hot-spot detection of HTS and maximize the sensing length for a given wavelength window of an interrogator.

AP9-7

Transport current characterisation of the magnetic field-angular dependence of the critical current density for bulk REBCO superconductors

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Computer modelling of bulk superconductors produced from rare-earth barium cuprates (REBCO) is important in the development of various applications, such as bearings, projected field magnets and levitation devices. Accurate models require input data that describes the critical current density and flux-flow exponent of the superconductor as a function of temperature, and magnetic field amplitude and orientation. However, at present there is a dearth of $J_c(T, B, \theta)$ and data $n(T, B,\theta)$ for REBCO bulks.

In this work, a technique is described to obtain such data via transport-I_c measurements using the SuperCurrent instrument at the Robinson Research Institute, which has been specifically developed to characterise the angle-, temperature- and field-dependence of critical current in HTS wires.

Superconducting bars with cross-sections of less than 5 mm^2 were cut from Ag-infused GdBCO bulks using a diamond wire band saw, and then mounted and polished to produce measurement samples. Four-point probe measurements of transport have then been performed using the SuperCurrent system, which enables measurements at a range of temperatures (down to ~15 K), and with applied fields of up to 8 T and over 360 degrees orientation. Preliminary measurements of REBCO bulks made using this method are reported, in particular, the highly anisotropic field dependence observed, in addition to significant temperature dependence of both self-field I_c and n-value.

AP10-1-INV

A novel ultra-high current density HTS magnet form

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Thanks to the progress in developing High-T_c Superconducting (HTS) wires and tapes, HTS magnets have shown superior performance over their LTS counterparts in terms of high operating field, high engineering current density, and wide operating temperature range. Traditionally, HTS magnets operate in series connected mode in which all coils transport the same current. Due to the fact that HTS wires have a very strong field and field angle dependence of critical current density, the operating current is limited by end portions of the magnet. Although optimized magnet designs such as multi-width coils have been proposed, the engineering current density is far from being maximized.

In this work, we propose a novel HTS magnet form with all coils operating in parallel. Large transport current is generated by a flux pump and will auto-distribute into individual coils thus making each coil working close to its critical current. We will show the ultra-compact design concept, development procedures, and some preliminary test result. It is expected that this work could provide some new perspective in developing ultra-high field HTS magnets.

Keywords: HTS magnet, Flux pump, parallel operation, ultra-high current

AP10-2-INV

Transformer-rectifier flux pumps at the Paihau-Robinson Research Institute

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High temperature superconductor (HTS) magnets have the potential to drive a range of world-changing technologies including Fusion reactors and high field (>23.5T) MRI/NMR magnets. Flux pumps are an enabling technology for the creation of the high current magnet power supplies necessary for this next generation of HTS magnets. HTS flux pumps utilize inherent superconducting properties to drive the charging mechanism that can use the high current capacity of modern coated conductors (>kA) and allows these currents to be generated using low electrical and cooling power.The Paihau-Robinson Research Institute has an extensive history exploring a variety of flux pumps – starting with travelling wave flux pumps [1–3] up to our recent work in transformer-rectifier flux pumps (TRFPs) [4,5]. We believe that TRFPs are ideally suited for high current (> 1 kA), relatively high inductance (>1mH) applications. In this talk, I will outline how we are improving the Technology Readiness Level (TRL) for application in systems and discuss our continuing work in TRFPs demonstrating:Development of a TRFP Simulink modelAs TRFPs transition from lab-based research to real world applications, the creation of a modelling infrastructure is essential. Accurate modelling can drive understanding and rapid design optimisation essential for prototyping real-world flux pumps. However, existing modelling techniques [6–8] do not integrate the magnetic or superconducting properties in a robust fashion. As will be shown, our Simulink technique allows all elements to be realistically embedded within the model enabling the production of qualitatively accurate data. Furthermore, the Simulink framework can model any TRFP topology and allows the addition of other superconducting properties (such as ac loss) or experimental variables (such as operating temperature).Conduction Cooled J_C (B) TRFPRecently, Paihau developed a new style of TRFP based directly on the J_C (B) characteristics of the HTS wire [4]. This work was conducted in liquid nitrogen; however, we anticipate that many real-world TRFPs will need to operate within conduction cooled systems. To this end, we have created the first J_C (B) TRFP in a conduction cooled system. I will present data outlining how the finite cooling power and operating temperature influence the pumping behaviour and will discuss design optimisation for conduction-cooled TRFPs.Scaling Conduction Cooled TRFPs to high currentsThe long-term goal is the creation of a conduction-cooled TRFP capable of achieving load currents greater than 10kA. This challenge will require precise thermal management and a thorough comprehension of the factors driving the rectification. To ensure complete understanding, we have explored the J_C (B) switching mechanism using finite element modelling and highly focussed experiments. This work has highlighted that the interplay between the superconducting and passive circuit elements can lead to significant asymmetrical behaviour. However, this asymmetry, if correctly harnessed, may prove beneficial for high current TRFPs.[1] Hoffmann C, Pooke D and Caplin A D 2011 Flux pump for HTS magnets IEEE Trans. Appl. Supercond. 21 1628–31[2] Hamilton K, Pantoja A E, Storey J G, Jiang Z, Badcock R A and Bumby C W 2018 Design and Performance of a "squirrel-Cage" Dynamo-Type HTS Flux Pump IEEE Trans. Appl. Supercond. 28[3] Mataira R C, Ainslie M D, Badcock R A and Bumby C W 2019 Origin of the DC output voltage from a high- Tc superconducting dynamo Appl. Phys. Lett. 114[4] Leuw B, Geng J, Rice J H P, Moseley D A and

Badcock R A 2022 A half-wave superconducting transformer-rectifier flux pump using J c (B) switches Supercond. Sci. Technol. 35 035009[5] Rice J H P, Geng J, Bumby C W, Weijers H W, Wray S, Zhang H, Schoofs F and Badcock R A 2022 Design of a 60 kA Flux Pump for Fusion Toroidal Field Coils IEEE Trans. Appl. Supercond. 32 1–5[6] Li C, Yang J, Shen B, Ma J, Gawith J, Ozturk Y, Geng J and Coombs T A 2020 A HTS Flux Pump Simulation Methodology Based on the Electrical Circuit IEEE Trans. Appl. Supercond. 30 1–5[7] Gawith J D D, Geng J, Li C, Shen B, Zhang X, Ma J and Coombs T A 2018 A half-bridge HTS transformer–rectifier flux pump with two AC field-controlled switches Supercond. Sci. Technol. 31 085002[8] Li C, Wang S, Jia H, He J, Li B and Coombs T A 2021 Impacts of the Saturated Transformer on the HTS Flux Pump IEEE Trans. Appl. Supercond. 31 1–4

Keywords: High temperature superconductors, Flux pumps, Superconducting magnets, Fusion energy

AP10-3

Design and Build of a 200 A Conduction Cooled HTS Dynamo for Superconducting Motor Field Coil Energisation

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A conduction cooled superconducting dynamo recently built at Robinson Research Institute provides 200 A current to energise the field coils of a 10 kW high speed superconducting motor. Unlike previously built superconducting dynamos, this example is engineered so the peak efficiency current range of the HTS dynamo matches the nominal operating current of the ReBCO motor field coils. In addition, this HTS dynamo is designed to operate inside a vacuum, without an iron yoke, and with a non-cryogenic rotor, reducing the overall cryogenic cooling load and improving coil energisation efficiency.

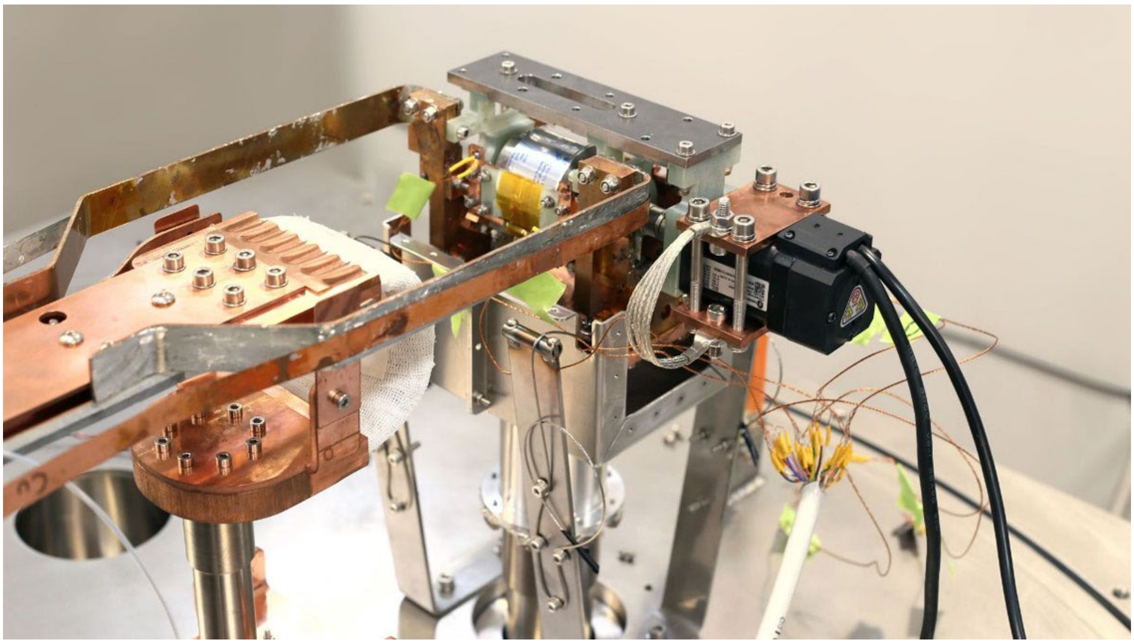
HTS dynamos are type of superconducting flux pump that enable wireless DC energisation of fully superconducting circuits. These devices utilise the non-linear E-J behaviour of a type-II superconductor to rectify the shielding current induced by permanent rotor magnets passing over a superconducting stator tape. This results in DC voltage along the tape length. Because the magnets and superconducting tape must rotate relative to each other, HTS dynamos are well suited to superconducting motor applications where efficient and reliable energisation of rotating field coils is required.

Conventional superconducting motor field coil energisation requires a current supply matched to the field coil operating current, and non-superconducting circuit components including sliding brushes and current leads that penetrate the cryogenic rotor envelope. Wireless energisation via HTS dynamo replaces each of these components with a lightweight and more cryogenically efficient alternative. Multi-kiloamp currents are induced in the fully superconducting field coil circuit from a low current source, removing the need for a high current DC supply. Non-superconducting cryogenic envelope penetrations are removed as the HTS dynamo transmits power wirelessly. As these are typically highly thermally conductive copper leads, their removal reduces the cryogenic cooling power required to maintain field coil operating temperature. Wireless power transmission also removes the need for sliding contacts between the field coils and their power source.

Previous work on HTS dynamos revealed yoke iron and liquid nitrogen drag to be large contributors to overall system losses. The newly developed HTS dynamo built at Robinson Research Institute has a yokeless design, and is conduction cooled in a vacuum to remove liquid nitrogen drag.

This presentation will introduce the HTS dynamo and its operating principle, illustrate the development process used to match the HTS dynamo output to the AC Homopolar motor field coil requirements, and describe the challenges of designing this conduction cooled device which has cryogenic and room temperature components in close proximity.

Keywords: Flux Pump, Coil Energisation, Current Supply, Brushless Exciter



AP10-4

Demonstration of a hybrid rotating-magnet rectifier HTS flux pump

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Superconducting rectifier flux pumps have been gaining attention as potential high current supplies for REBCO magnets, due to their small footprint and thermal efficiency. Separately, HTS dynamos have recently been demonstrated to output kA currents, and can be introduced into rotating machine designs without penetrating the cryogenic environment. Here, we present a novel mechanically-rectified flux pump topology that combines the advantages of both types of device. We report the design, build and 1st experimental validation of this hybrid concept.

This new class of high-Tc superconducting flux pump employs permanent magnets mounted on a simple rotor to induce an ac emf in an HTS stator coil, which is then rectified by periodic variation of the resistance of a parallel bridge tape. The focus of the device design are the steel rotor and stator which direct magnetic flux through both the induction coil and the separate switching bridge. The relative timing of flux through the coil and bridge is determined by the stator geometry, and can be adjusted to maximise the rectified DC output. An experimental prototype device has been demonstrated by charging a 77.6 μH superconducting magnet to 12.8 A in 73 s. Results from experiments with one and two rotor magnets are presented, which show evidence of two different modes of operation: (i) self-rectification and (ii) field-switched Jc(B) rectification. The maximum load current is found to increase non-linearly as rotor speed increases, plateauing near 450 RPM. This flux pump design has the potential to be operated atr very low heat load in future machine designs, by placing the magnets outside of the cryostat.

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Keywords: HTS flux pump, HTS magnet, Efficiency

AP10-5

A Full-wave HTS Transformer-Rectifier Using $J_c(B)$ Switching: Modelling and Experiments

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High-field superconducting magnets made possible by advances in commercial High-temperature Superconductor (HTS) production are of interest in a range of applications. These include magnetically-confined thermonuclear fusion, high-power electric motors, medical resonance imaging, and other diagnostic applications. Such magnets can be energized efficiently using flux pumps. Flux pumps are high-current superconducting power supplies for energizing inductive loads. Transformer-rectifier flux pumps benefit from smaller input currents to reduce cryogenic heat load requirements and can charge and maintain large currents in superconducting magnets. This makes transformer-rectifier flux pumps desirable to reduce the size, cost, and cryogenic footprint of high-field magnet applications.

Here, we report on a new HTS flux pump using a full-wave, centre-tap transformer-rectifier circuit topology, rectified utilizing applied DC magnetic field switches. Experimental results are reported and compared to a numeric, electrical model. We then present physical interpretations of these results in the context of achieving higher currents.

AP10-6

Increment of levitation stability in the magnetic circuit design of the HTS magnetic bearing rotor

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Magnetic levitation using the pinning force of a high-temperature superconductors (HTS) has the advantage which is stable levitation without control [1], [2]. The magnetic circuit design of the HTS magnetic bearing to increase pinning force is studied. The magnetic bearing system uses the HTS on the stator and the rotor on the rotor. The HTS bulk material is yttrium barium copper oxide. The HTS diameter is 80 [mm] and its thickness is 20 [mm]. The rotor is levitated by the pinning force of the HTS. The HTS is installed on the stainless stage, and the acrylic plate for a spacer is installed on the HTS. The rotor is set on the spacer, which is placed at the center of the HTS. Liquid nitrogen is poured into the stainless vessel until the HTS is immersed therein, and the HTS is retained in a magnetic field for 20 min (field cooling). Once cooling is complete, the spacer is removed and the rotor is levitated. Fig.1 shows the structure of two layer ring-type rotor, yoke-equipped ring-type rotor and the magnetic flux distribution of that. The neodymium magnet is used for the rotors. The two-layer ring-type rotor comprises a cylindrical and a ring-type permanent magnet, and the flux at the top side dose not interlink sufficiently with the HTS[3]-[5]. The yoke-equipped ring-type rotor is introduced to increase the flux-use rate to use the flux at the top side. By concentrating the flux of the rotor on the HTS, the pinning force of this rotor increases. In designing the magnetic circuit of the rotors, the flux interlinked with the HTS surface increased and focused to the outer side of the HTS. The permanent magnet volumes of the two-layer ring-type rotor and the yoke-equipped ring-type rotor are almost the same. The experiment is studied the levitation gap g=8,10 [mm]. When the levitation gap is 8 [mm], the total flux of the yoke-equipped ring-type rotor interlinked with the HTS surface increases by 54.9% compared with the two- layer ring-type rotor. The levitation force increases by 24.4% compared with that one. The guidance force increases by 69.5% compared with that one. When the levitation gap is 10 [mm], the total flux of the yoke-equipped ring-type rotor interlinked with the HTS surface increases by 68.4% compared with that one. The levitation force increases by 24.8% compared with that one. The guidance force increases by 62.6% compared with that one. By equipping the yoke to the rotor, the total flux increases, and the pinning force also increases. As the result, the maximum amplitude is decreased at the resonance point in the rotational characteristics, and the rotor stability increases. When the levitation gap is 8 [mm], the maximum amplitude of the yoke- equipped ring-type rotor decrease by 61.2% compared with that one. When the levitation gap is 10[mm], the maximum amplitude of the yoke-equipped ring-type rotor decrease by 59.0% compared with that one. This is because by concentrating the flux on the outer side of the HTS, the force that suppresses vibration during resonance has increased. By improving the magnetic circuit, the levitation force, the guidance force, and the rotational characteristics of the yoke- equipped ring- type rotor are improved. As the result, the stability of the rotor has improved.

References

[1] F. C. MOON, “SUPERCONDUCTING LEVITATION”, JOHN WILEY & SONS, NEW YORK, (1994)

[2] J. Hull, M. Murakami, “Apprications of bulk high temperture superconductors”, in Proc of IEEE,

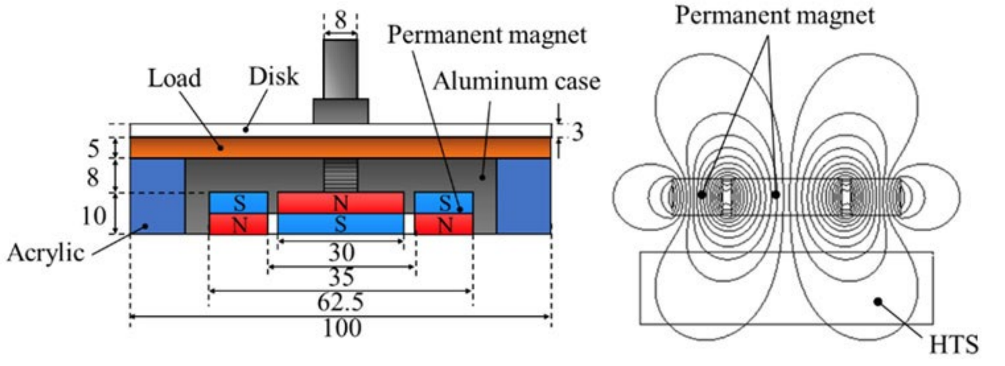
vol. 92, no. 10, October 2004, pp1705-1718

[3] S. Sakai, K. Oguni, S. Ohashi, “Effect of the magnetic configuration on the rotational motion in the attractive type HTS-permanent magnet hybrid bearing”, IEEE Trans on Applied Superconductivity, vol. 26, no.4, 3601204, June 2016.

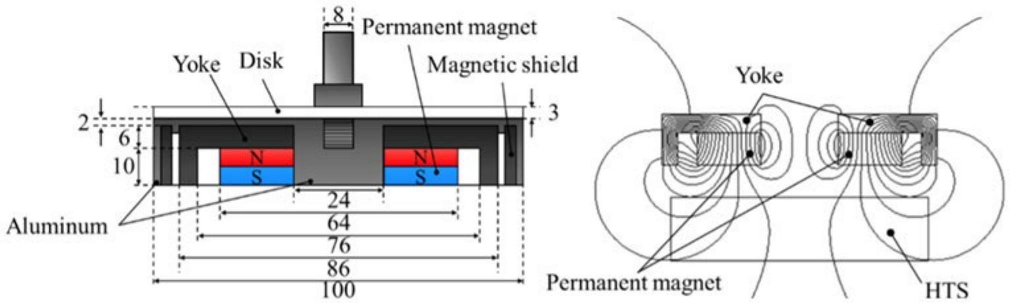
[4] T. Minami, S. Sakai, S. Ohashi, “Improvement of stability against vibration at the mechanical resonance in attractive type HTS permanent hybrid magnet bearing.”, 2016 IEEE Region 10 Conference (TENCON2016), 16657805, 2016, pp3294-3297.

[5] S. Takimura, T. Arai., T. Minami, S. Ohashi, “Basic characteristics of the yoke equipped rotors in the magnetic bearing using HTS pinning effect”, IEEE Xplore Digital Library IEEE, 12th International Symposium on Linear Dives for Industry Applications (LDIA2019), 8770991, 2019.

Keywords: HTS, Pinning force, Magnetic bearing, Permanent magnet



(a) Two-layer ring-type rotor



(b) Yoke-equipped ring-type rotor

Fig.1 The structure and the flux distribution of the rotors

AP10-7

Numerical evaluation of rotational loss characteristics of low-speed rotating superconducting magnetic bearings for various levitation forces

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Superconducting magnetic bearings (SMBs)[1] generally consist of a rotor containing permanent magnets or magnetic materials and a stator containing bulk superconductors. Since the pinning effect levitates the rotor, there is no mechanical contact. Therefore, the use of this structure in flywheels[2], cryogenic pumps[3], and bearings for satellites[4] is being considered. We are particularly interested in bearings for onboard satellites.

The bearings for satellites are about 400 mm in diameter and are expected to operate at 72 rpm, and the allowable heat generation is minimal (4 mW). We have proposed an SMB structure consisting of a rotor composed of ring-shaped segmented permanent magnets and an iron yoke, and a stator composed of ring-shaped segmented bulk superconductors. The permanent magnets are parallel magnetized. Electromagnetic losses occur in such a structure. First, a magnetic field is generated on the rotor side. Next, a superconducting current flows in response to the magnetic field on the stator side. At this time, superconducting losses occur on the stator side. A magnetic field created by the superconducting current is generated. This magnetic field generates eddy currents. At this time, eddy current loss and iron loss are generated on the rotor side. To optimize the design of SMBs to suppress these electromagnetic losses, it is important to investigate their rotation loss characteristics.

We developed a FEM analysis model of the SMB and analyzed the rotational loss for various levitation forces. We used a model that combines the H-φ formulation and A-V formulation as a three-dimensional electromagnetic field analysis. The φ formulation is used to calculate the magnetic field generated by the rotor, the H-φ formulation to calculate the current induced in the superconductor of the stator, and the A-V formulation to calculate the eddy currents induced in the stator by the magnetic field due to the superconducting current. The analysis is performed using COMSOL Multiphysics, a general-purpose physics simulation software, and an n-value model for the superconductor's current-voltage characteristics. This study is mainly concerned with the electromagnetic interpretation of eddy current losses.

References

[1] J. R Hull, Superconducting Science and Technology, Vol. 13, No. 2 (2000), pp. R1-R15.
[2] K. Demachi, et al., Physica C: Superconductivity, Vol. 426-431, Part 1 (2005), pp. 826-833.
[3] Q. Lin, et al., IEEE Transaction on Applied Superconductivity, Vol. 22, No. 3 (2012).
[4] M. Hazumi et al., Proc. of SPIE, Space Telescopes and Instrumentation 2020: Optical, Infrared, and Millimeter Wave, Vol. 11443 (2020), 114432F.
[5] A. Arsenault et al., IEEE Transactions on Applied Superconductivity, Vol.31, No.2 (2021).

Keywords: Superconducting magnetic bearing, Rotational loss, Finite Element Analysis