27th International Symposium on Superconductivity, ISS 2014

Eddy Current Loss Induced in Aluminum Thermal Conduction Strips for ASPCS Coils Indirectly Cooled by Liquid Hydrogen through Thermo-Siphon System

Narumi Ota*, Masashi Katsura, Kennosuke Ando, Tomoaki Takao, Takakazu Shintomi, Yasuhiro Makida, Takataro Hamajima, Makoto Tsuda, Daisuke Miyagi, Hiroshi Tsujigami, Shizuichi Fujikawa, Toshiaki Semb, and Katsuya Iwaki

*Sophia University, Tokyo 102-8554, Japan
bHigh Energy Accelerator Research Organization, Oho, Tsukuba, Ibaraki 305-0801, Japan
cTohoku University, Aoba-ku, Sendai, Miyagi 980-8579, Japan
dIwatani Corporation, Minato-ku, Tokyo 104-8058, Japan

Abstract

To promote renewable energy sources, we proposed a new system called the Advanced Superconducting Power Conditioning System (ASPCS), which consists of Superconducting Magnetic Energy Storage System (SMES), Electrolyzer, and Fuel Cell, and is also combined with a liquid hydrogen station for vehicles. The SMES plays a role to compensate the fast fluctuations generated by the renewable energies. In case of the ASPCS with a capacity of 5 MW, we designed the 50 MJ-class SMES composed of 4 solenoid coils. The winding of the solenoid coils is double pancake and a basic coil is 2 m in diameter and 0.5 m in height. Each SMES coil is wound with MgB2 conductor and indirectly cooled at 20 K by liquid hydrogen flowing through a thermo-siphon cooling system. Pure aluminum strips are inserted between the double-pancake coils and the pure aluminum plates gathering the strips lead to liquid hydrogen pipes. This scheme enables the strips and the plates to transfer the heat load in the coils to the cooling pipes and keep the coils at low temperature. On the other hand, we must consider that the strips generate eddy current loss which is strongly affected by a width of the strips. At the same time as the primary study of the SMES coils, we experimented on the thermo-siphon cooling system and investigated the relationship between the heat load and the heat extraction ability of the cooling system. The experiments showed that the cooling system could proficiently function. The estimation of eddy current loss from the particular cooling aluminum strips for the SMES in the ASPCS is reported with the results of the thermo-siphon driving experiment.

© 2015 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Peer-review under responsibility of the ISS 2014 Program Committee

Keywords: MgB2; SMES; renewable energy; hydrogen

* Corresponding author. Tel.: +81-3-3238-3326; fax: +81-3-3238-3326.
E-mail address: narumi.ohta@gmail.com
1. Introduction

From the point of view of environmental problems, it is an urgent issue to reduce carbon dioxide emissions. Thus the introduction of renewable energies such as through wind and photovoltaic power generation has been accelerated because these sources are clean and abundant. However, the power of such renewable energy sources depends on the weather conditions so their output is unstable. If a large number of fluctuating sources are installed, power networks become unstable. In order to compensate these fluctuations, we propose a new system called an Advanced Superconducting Power Conditioning System (ASPCS), which is composed of a SMES system, a fuel cell/electrolyzer (FC-EL) system, and DC/DC and DC/AC converters [1], [2]. The ASPCS is also set next to a liquid hydrogen station for fuel cell vehicles (FCV), which are planned to install more than 3500 by 2030 [3]. The liquid hydrogen station will also serve as a liquid hydrogen storage facility. Therefore, it is synergistically effective to use liquid hydrogen as a cryogen to cool the SMES coil for the ASPCS.

The SMES coil is made from MgB$_2$ conductor, whose $T_c$ is 39 K, and cooled at 20 K by liquid hydrogen. Taking into consideration of the future-properties of MgB$_2$ conductor, we designed the SMES coil for the ASPCS [4]. It is necessary and important to examine AC loss occurring in the SMES coil, so in this paper we provide an estimate of the eddy current loss induced in the cooling plates.

2. ASPCS and SMES

2.1. Concept of ASPCS

The concept of ASPCS is shown in Fig. 1. The fluctuations of electric power can be broken down into two kinds; short-term ones lasting for minutes and less, and medium-term ones typically lasting for hours, for which the ASPCS should smooth the fluctuating power. The medium-term fluctuations are compensated by FC-EL, and the short-term ones by SMES. In the former conceptual design study for the ASPCS system, a 5 MW wind farm was targeted and the required SMES capacity was found to be 50 MJ.

2.2. Conceptual design of 50 MJ SMES coil

In order to reduce the leakage magnetic field, the SMES is made up by the four solenoid coils and they are arranged such that the polarity of their magnetic field is reversed alternately. In addition, the coils are placed 0.2 m apart to lessen the electromagnetic forces. The designed maximum magnetic field is 5 T at 20 K in consideration of the critical current properties of MgB$_2$ conductor to be expected through development in the near future. The estimation of the production costs, the transportation of these coils from a factory to an installation site, and the leakage magnetic field, depend on the size and design of a basic coil.

The size of the basic coil is 1.45 m ID, 1.93 m OD and 0.521 m high, and the coil winding is double pancake. The maximum operating voltage and current are 1 kV and 2.2 kA, respectively. The coil is indirectly cooled by a thermo-siphon system to minimize risks due to the flammability of liquid hydrogen. A thermo-siphon cooling pipe starts at the bottom of the LH$_2$ reservoir, goes down to the lowest point without incoming heat load, and then returns up to the top of the reservoir. At the upward flow pipes, the heat load conducted through aluminum strips is transferred into liquid hydrogen, and then the hydrogen bubbles float to top of the reservoir, liquid being supplied from the bottom [5].

3. AC loss of SMES coil for ASPCS

3.1. Eddy Current Loss Induced in Aluminum Conduction Strips for 50 MJ SMES coil

To keep the SMES coil at low temperature and transfer heat load due to AC loss to the thermo-siphon pipes, each double-pancake coil is held between pure aluminum strips. The pure aluminum plates gathering the strips in Fig. 2 are thermally-contiguous to the heat exchange plates. The HEX plates are also in contact with the pipes. As shown in Fig. 2, the aluminum plates are designed two halves and have many slits to reduce the eddy current loss. The eddy current loss induced in the strips is strongly affected by the width $w$: the narrow the width, the smaller the loss.
We previously calculated the eddy current loss for 50 MJ SMES coil analytically, and reported it in reference [5]. However, this time, the loss was estimated by FEM. The magnetic distribution is formed inside a coil. Since the full 50 MJ SMES coil is the four-pole configuration, the distribution is also affected by the mutual effect of the basic solenoid coils. The losses can therefore be estimated more precisely by using FEM.

According to the result of FFT analysis, almost all of the SMES input and output power spectrum is covered within the frequency range from 0.001 Hz to 0.05 Hz, and thus the loss at 0.05 Hz of sine-wave power current frequency is examined because it is proportional to the square of frequency. The thickness of aluminum strips and plates is 0.2 mm, the slit length is 190 mm and the width is 10 mm. We analyzed all magnetic distribution of the surface on which aluminum plates and strips were installed. From the result of this FEM analysis, the total amount of the loss for the 50 MJ SMES coil is 198 W with the width of 10 mm at 0.05 Hz.

The width affects increasing temperature as well as the loss. The relationship between the temperature $T_{in}$ of inner side of the basic coil and the one $T_b$ of the junction with the liquid hydrogen line is estimated by the simplified equation below (1) [6]:

$$T_{in}^2 - T_b^2 = \frac{(2\pi B_\phi)^2}{L_0} \left( \frac{2}{27} (r_n - r_o)^2 + \frac{1}{90} \frac{w^2}{(r_n - r_o)^2} - \frac{1}{36} \frac{l^2}{l_s} \right) w^2$$

where $B_\phi$ is the magnetic flux density at the inner coil, $l$ is the length from the end of the slits to the outer coil, $r_o$ is the point at which the magnetic flux density is zero, $r_n$ is IR, $l_s$ is the perimeter of the aluminum plates and $L_0$ is Lorenz number.

The magnetic flux density reaches its peak at the innermost point on the middle plane of the coil and according to the equation (1), the temperature is 22.6 K on the aluminum strips and plates on this surface. For the further investigations, it is necessary to estimate the temperature gradient accurately and determine the suitable parameters for the aluminum strips and plates.

### 3.2. Cooling and Excitation Test using Model System

To validate the cooling technology for an SMES coil which is indirectly cooled via a thermo-siphon system, we made a 10 kJ model coil with a system as shown in Fig. 3, and carried out a test.

The model coil was made from Bi2223, and its ID, OD and height are 100 mm, 193.8 mm, and 56.6 mm, respectively. As a first step, we investigated the driving ability of the cooling system with the input power which was provided by attaching a heater to the HEX. This test was performed using liquid hydrogen and liquid helium, respectively. In case of liquid hydrogen, it was figured out that the cooling system could proficiently function up to 230 W input power as shown in Fig. 4.

Then, we also carried out the excitation current test only with liquid helium to find out whether the AC loss could be measured, prior to a test with liquid hydrogen. The coil was successfully excited up to its nominal current of 200 A, which was the rated coil current. When the operating current increased and decreased rapidly, the changes of temperature were monitored as shown in Fig. 5. The increase in temperature of the HEX was approximately 1.2 K and so from the result of Fig. 4, it could be assumed that the AC loss was 1.5 W.

This AC loss is the sum of the eddy current loss and the hysteresis loss. The eddy current loss occurs...
from the aluminum strips and the coil wire. To separate the components of these losses and estimate the eddy current loss due to the aluminum strips, we are analyzing the AC loss for the 10 kJ model coil alone. We are planning to experimentally study about AC loss and cooling capability of the model system soon.

4. Summary

To use renewable energy sources effectively, we proposed the ASPCS, composed of a combined SMES and EL-FC hydrogen system, working together with a liquid hydrogen station. The SMES coils wound with MgB$_2$ conductor are indirectly cooled at 20 K by liquid hydrogen flowing through a thermo-siphon cooling system to avoid problems due to its flammability, and the thermo-siphon circulation removes the heat load caused by AC loss. Taking into account of the mutual effect on the magnetic field distribution due to its four-pole configuration, the eddy current loss in the thermal pure aluminum strips and plates in contact with the pipes has been calculated; when the thickness of aluminum strips and plates is 0.2 mm, the slit length is 190 mm and the width is 10 mm, the total loss for the 50 MJ SMES coil is 198 W at 0.05 Hz.

We also investigated the efficiency of the thermo-siphon cooling system experimentally with the input power provided by attaching a heater to the line through which liquid hydrogen flows, and the ability was found to be 230 W. Then, throughout the excitation current test with Bi2223 coil cooled by liquid helium, it appeared to measure AC loss and thus the test with liquid hydrogen is prepared for.

Acknowledgements

This work is supported by the Advanced Low Carbon Reduction Technology R&D of the Japan Science and Technology Agency.

References

[1] T. Hamajima et al., Application of SMES and fuel cell system combined with liquid hydrogen vehicle station to renewable energy control, IEEE Trans. Appl. Supercond. 22 (3) (2012) 5701704
[2] T. Shintomi et al., Design study of MgB$_2$ SMES coil for effective use of renewable energy, IEEE Trans. Appl. Supercond. 23 (3) (2013) 5700304
[3] Feasibility study in response of hydrogen carriers in technology development of system to produce, transport and store hydrogen, 2009, NEDO report P08003.
[4] N. Ota et al., Design Study of SMES System Using MgB$_2$ Conductors for Compensating Fluctuation of Renewable Energy, Proc. ICEC 24 & ICMC 2012, pp.533-536, 2012
[5] Y. Makida et al., Design study of the cooling scheme for SMES system in ASPCS by using liquid hydrogen, Physica C 494 (2013) 208-212
[6] Private communication with Y. Makida