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Advanced Superconducting Power Conditioning System for Effective Use of Renewable Energy

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Abstract. In order to use effectively renewable energy sources, we propose a new system, called Advanced Superconducting Power Conditioning System (ASPCS) that is composed of Superconducting Magnetic Energy Storage (SMES), Fuel Cell-Electrolyzer (FC-EL), hydrogen storage and dc/dc and dc/ac converters in connection with a liquid hydrogen station for fuel cell vehicles. The ASPCS compensates the fluctuating electric power of renewable energy sources such as wind and photovoltaic power generations by means of the SMES having characteristics of quick response and large I/O power, and hydrogen energy with FC-EL having characteristics of moderate response and large storage capacity.

The moderate fluctuated power generations of the renewable energy are compensated by a trend prediction with the Kalman filtering algorithm. In case of excess of the power generation by the renewable energy to demand it is converted to hydrogen with EL. On the contrary, in case of shortage the electric power is made up with FC. The faster fluctuation that cannot be compensated by the prediction method is effectively compensated by SMES. In the ASPCS, the SMES coil with an MgB_2 conductor is operated at 20 K by using liquid hydrogen supplied from a liquid hydrogen tank of the fuel cell vehicle station. The necessary storage capacity of SMES is estimated as 50 MJ to 100 MJ depending on the prediction time for compensating fluctuation of the rated wind power generation of 5 MW. As a safety, a thermo-siphon cooling system is used to cool indirectly the MgB_2 SMES coil by thermal conduction.

The concept of the ASPCS and the design study of the SMES are reported.

Key words

Liquid hydrogen, SMES, renewable energy, fuel cell and electrolyzer, MgB_2 superconductor.

1. Introduction

It is an urgent issue to reduce carbon-dioxide, and hence renewable energy, that is environmentally friendly, should be supplied as sources of a large amount of the electric energy. The wind and photovoltaic power generations are expected as promising renewable energy sources because they are clean without carbon dioxide and out of anxiety of exhaustion. From the energy security point of view, the renewable energy sources become more and more important.

Recently the introduction of those energy sources becomes quite rapid and surprisingly increasing. However, they have a demerit of unstable power source depending on the weather. The installation of a large amount of such sources makes electric power networks unstable, and then it is required to install some kinds of measures for buffering the fluctuation.

Hydrogen as secondary energy is also clean and renewable energy in utilization of the fuel cell (FC) and the electrolyzer (EL). Hydrogen has a large storage capacity and it is effective to use it as a buffer of the fluctuation of the renewable energy. Moreover, it is expected for hydrogen stations for FC vehicles to become popular in the near future [1].

In order to compensate the fluctuation of the renewable energy sources and use them effectively, we propose a new system called an Advanced Superconducting Power Conditioning System (ASPCS) that is composed of superconducting magnetic energy storage (SMES), FC-EL, hydrogen storage, and dc/dc and dc/ac converters. The ASPCS is combined with liquid hydrogen stations for FC vehicles.

Recently superconducting devices using MgB_2 conductors have been developed [2]–[4] and possibility of MgB_2 magnets by cooling liquid hydrogen was proposed [5], [6]. Moreover, the studies on such magnets for power applications have been carried out [7]–[12].

The concept of the ASPCS and the design study of the SMES with MgB_2 conductors that is one of the important componets of the ASPCS system are reported.

2. Concept of Advanced Superconducting Power Conditioning System (ASPCS)

The ASPCS is composed of SMES with MgB_2 conductor cooled at 20 K using cryogen of liquid hydrogen, FC-EL, dc/dc and dc/ac converters, and a liquid hydrogen storage of a vehicle station as shown in Fig. 1. The ASPCS is connected to wind and photovoltaic power generators to compensate their fluctuations. The proposed system is assumed to use dc bus lines, and each component is connected to each other through dc/dc and dc/ac converters. In this study, it is fixed that the wind power generation is 5 MW and the output power of SMES is 1 MW.

The wind power generation, for example, contains a moderate-term fluctuations of a few tens minutes and over and a short-term ones of several minutes and below. The moderate-term fluctuations can be compensated with FC-EL by a trend prediction using the Kalman filtering

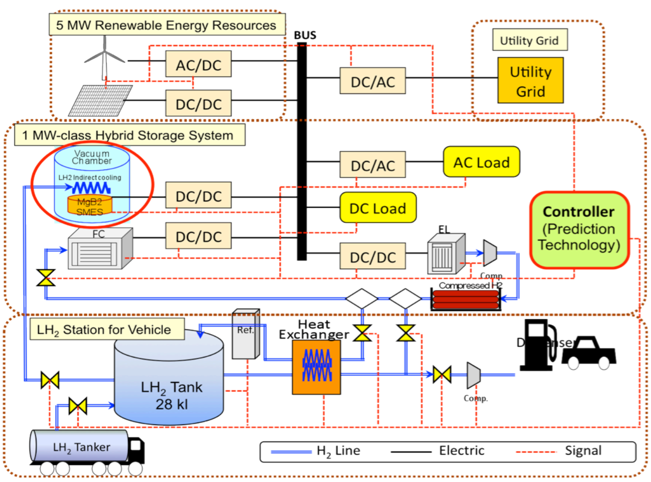

Fig. 1. The concept of the Advanced Superconducting Power Conditioning System (ASPCS).

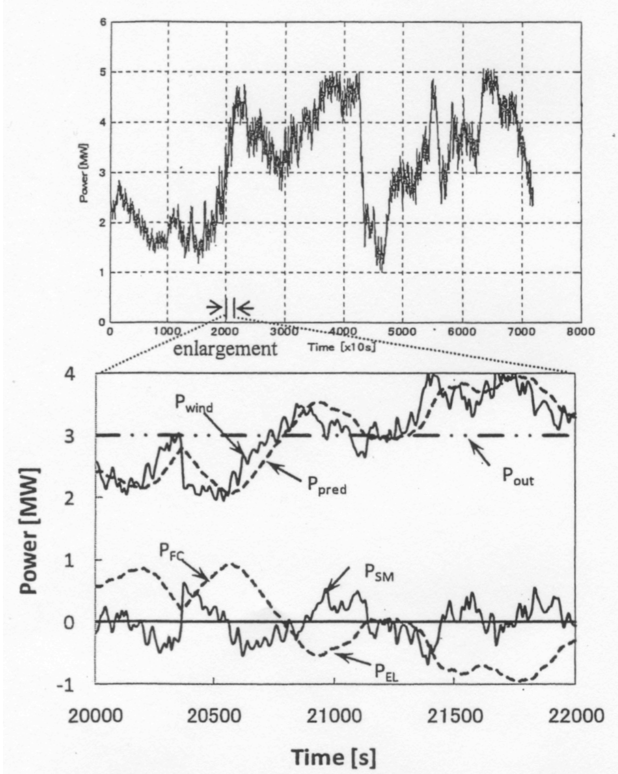

Fig. 2. The typical waveforms of thewind turbine power generation (1 MW x 5 sets) and the compensation of the fluctuation. P_{wind}: actual wind power, P_{pred}: predicted wind power, P_{out}: power demand, P_{SM}: SMES compensation power, P_{EL}: converted power to hydrogen with EL, and P_{FC}: generated power with FC.

algorithm [11]. The compensated moderate-term power generation over the electric power demand is converted to hydrogen with EL and stored into a high pressure gas vessel or the liquid hydrogen reservoir of the vehicle station. On the contrary, the required electric power is generated with FC in case of shortage to the power demand. Figure 2 shows the compensation of the wind power generation. The wind power generation P_{wind} is predicted as P_{pred} by the Kalman filtering algorism. In case that the P_{pred} is less than the power demand P_{out}, the necessary electric power P_{FC} is generated with FC. On the contrary, the surplus power P_{EL} is converted to hydrogen with EL in case that P_{pred} is over P_{out}. Then the moderate-term fluctuations can be compensated as shown in the figure.

On the other hand, the short-term fluctuations, that cannot be predicted, are to be compensated with the SMES unit that has characteristics of fast response and large I/O power. P_{SM} is input and output power of the SMES unit to compensate the fast fluctuations.

3. Optimization of SMES Capacity

The input and output energy of SMES is given by

$$E_{SMES} = \int \left| P_{wind} - P_{pred} \right| dt \qquad (1)$$

The necessary storage capacity of SMES for the compensation depends on the prediction time and the necessary capacity becomes smaller for the shorter

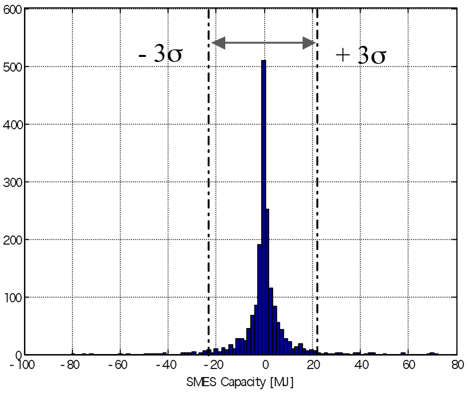

Fig. 3. Histogram of SMES input and output energies in case of the prediction time of 10 seconds. In order to cover the compensation with ± 3σ (99.7%), the necessary I/O energy capacity of SMES is 45 MJ.

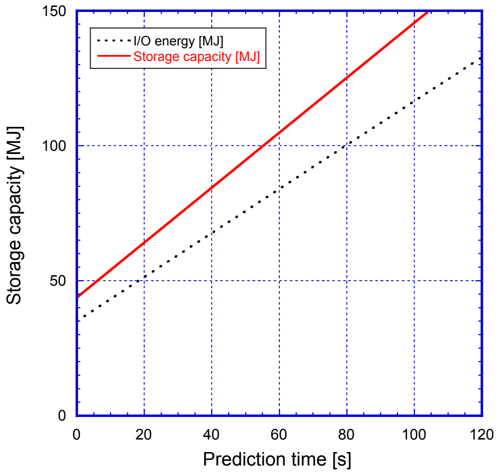

Fig. 4. Necessary storage capacity and I/O energy of SMES vs. the prediction time. In case of the prediction time of 10 seconds, the necessary SMES storage capacity is 55 MJ.

prediction time. The prediction time is related to the start-up time of FC. We assume to use PEFC which has the start-up time of 10 seconds from the standby and 60 seconds from the cold start.

We estimated the distribution of the I/O energy of SMES given in Eq. 1 for the typical wind power waveform in case of the prediction time of 10 seconds as shown in Fig. 3. The histogram shows almost the normal distribution. When it is assumed that SMES covers the I/O energy of ± 3σ in the distribution, the SMES I/O capacity is 45 MJ. Since 80% of the maximum stored energy is usually available, 50 MJ-class SMES is required. As the same manner, 100 MJ-class SMES is necessary in case of the prediction time of 60 seconds. The relation of the SMES I/O energy and the necessary SMES storage capacity versus the prediction time is shown in Fig. 4.

4. Design of SMES

A. Properties of MgB_2 Conductor

The SMES coil is made by an MgB_2 conductor, whose T_c is 39 K, cooled at 20 K using liquid hydrogen. In consideration of the I_c – B characteristics of the MgB_2 conductors at 20 K, the maximum acceptable magnetic field is limited to 2.5 T at this moment. However, it is expected that the I_c – B properties will be improved in the near future. Figure 5 shows the I_c – B properties of the existing MgB_2 wire developed by Hyper Tech Research Inc. at 20 K and 25 K [13]. Though I_c is 100 A at 2 T and 20 K at present, the target I_c is expected to be 100 A at 5 T and 20 K. Using these I_c – B properties, we designed two types of SMES coils, that is to say, a solenoid type and a toroid type.

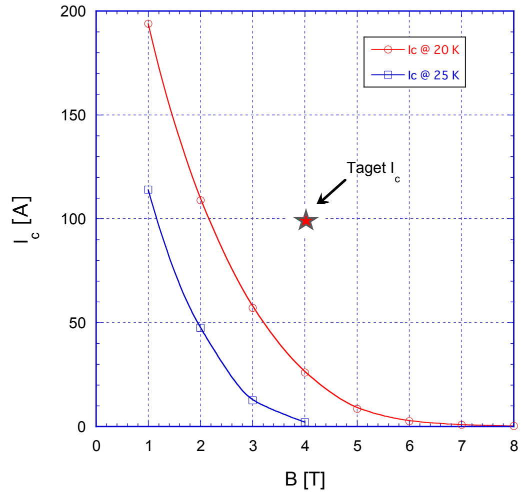

Fig. 5. The I_c – B properties of the existing MgB_2 wire. The properties of the MgB_2 conductor is expected to improve in the near future at the target value.

B. Solenoid Coil

We designed the 50 MJ SMES solenoid coil that is composed of four poles with a basic coil of 10 MJ. This configuration has merits of fabricating a smaller scale unit and reduction of the leakage magnetic field. The design has been performed for 2 T solenoid and 5 T solenoid. The former is conservative using the existing wire and the latter is expecting.

In case of the 2 T solenoid, the coil size becomes much larger and then it has to take into consideration the transportation of the completed coil from a factory to a site. The SMES is consisted of four basic coils each of which has the inner diameter, the outer diameter and the height of 1.45 m, 1.75 m and 3.1 m, respectively. The calculated ampere-turns of the basic coil is 5.6 MAT. The maximum coil voltage is selected as 1 kV for safety and the available SMES energy is assumed to be 80% of the maximum stored energy. Since the SMES system has to be operated at the output power of 1 MW in the whole range from the minimum stored energy of 8.8 MJ to 44 MJ, the maximum coil current becomes 2.2 kA.

The basic coil is made by the double pancake winding and pure aluminum plates are inserted between the double pancakes for conduction cooling with a thermo-siphon cooling system as described in the following

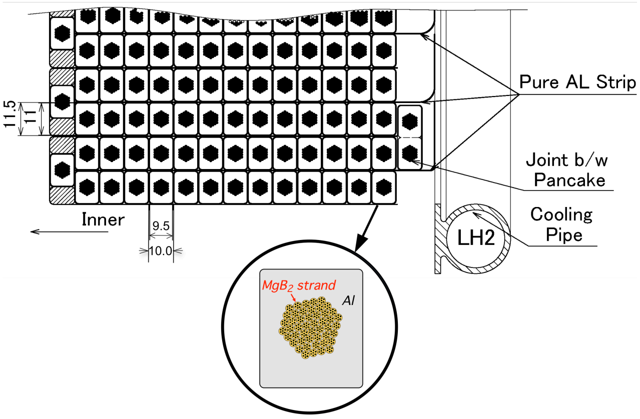

Fig. 6. The coil configuration of the 10 MJ basic coil. The coil is cooled by conduction with the liquid hydrogen cooling pipe which is a component of the thermo-siphon cooling system.

chapter. The cable for the coil is made by co-extruding stranded MgB_2 wires with pure aluminum. The coil configuration is shown in Fig. 6.

In case of the 5 T solenoid, the coil size becomes much compact. The coil is designed to have a minimum quantity of the MgB_2 conductor. The coil diameter is almost same as that of the 2 T coil. However, the coil height is one-sixth of that of the 2 T coil. The amount of the conductor for the 5 T coil is also two-third of that of the 2 T coil.

The design parameters are shown in Table I.

Table I. - Parameters of SMES solenoids for 2 T and 5 T

Type		2 T	5 T
Power	Constant output power	1 MW	
	Max. operating current	2.2 kA	
	Max. operating voltage	1 kV	
Basic coil	Stored energy	10 MJ	11 MJ
	Magnetic motive force	5.6×10^6 A	3.3×10^6 A
	Coil inner diameter	1.45 m	1.6 m
	Coil outer diameter	1.75 m	2.0 m
	Coil height	3.1 m	0.485 m
	Operating temperature	20 K	
4-pole coil	Stored energy	44 MJ	50 MJ
	Max. flux density	2.39 T	5.01 T
	Hoop force	25.4 MN	28.7 MN
	Compression force	3.7 MN	12.4 MN
	Centripetal force	1.26 MN	2.54 MN
Cable	Material	MgB_2	
	Amount of conductor	113×10^6 Am	75×10^6 Am

C. Toroid Coil

The SMES coil of 100 MJ is designed by the toroid type. The magnetic forces, the temperature stability of the coil and the coil protection are taken into consideration. The cable-in-conduit conductor is used as shown in Fig. 7. In consideration of the future development of the MgB_2 conductors, the size of the 5 T coil becomes almost half of that of the 2 T coil as shown in Fig. 8. It is estimated that the necessary amount of the superconductor of the 5 T coil becomes 74% of that of the 2 T coil. In addition, the

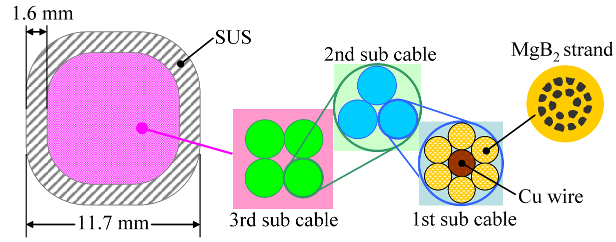

Fig.7. The conductor for the 100-MJ toroid SMES coil. Total of 96 MgB_2 wires consists of the cable-in-couduit conductor.

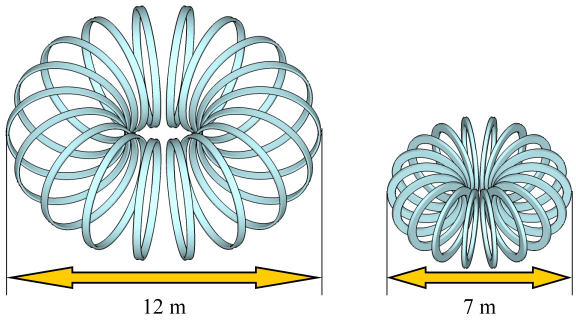

Fig. 8. Comparison of the size of the 2 T and 5 T SMES toroid coils.

leakage of the magnetic field becomes smaller in comparison to the 2 T toroid. The magnetic forces of the 5 T toroid coil are acceptable. The unit coil of the toroid is also made by the double pancake winding, and cooled indirectly with the thermo-siphon system as same as the solenoid type.

The design parameters of the SMES toroids are shown in Table II.

Table II. - Parameters of SMES toroids for 2 T and 5 T

Type	2 T	5 T
Max. stored energy	100 MJ	106 MJ
Constant output power	1 MW	
Max. operating current	4 kA	
Max. operating voltage	2 kV	
Toroid aspect ratio	0.6	
Major radius	3.68 m	2.0 m
Minor radius	2.21 m	1.2 m
Unit coil outer radius	2.28 m	1.49 m
Unit coil width	0.41 m	0.14 m
Number of unit coils	18	
Magnet motive force	13.8×10^6 A	18×10^6 A
Amount of conductor	195×10^6 Am	152×10^6 Am
Max. hoop stress	72 MPa	114 MPa
Centripetal force	30 MN	68.6 MN

5. Cooling System of SMES Coil

Liquid hydrogen, which has a high-flammability range, needs to be strictly adhered to keep special handling methods of storage and transport in order to avoid critical accidents. These safety measures for dealing with liquid hydrogen have to be applied not only outside air environment but also inside vacuum insulating. All high current circuits composed of the SMES coil system with

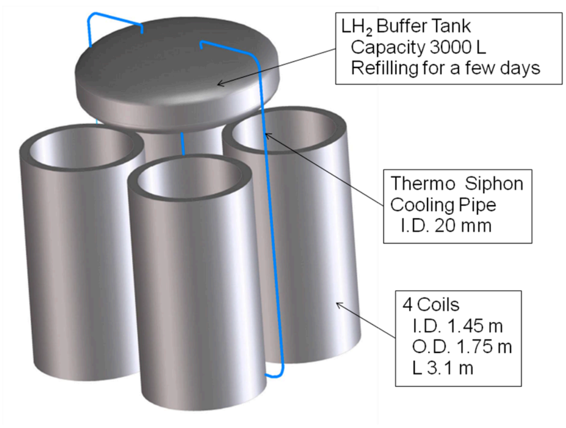

Fig. 9. MgB_2 four-pole coil and thermo-siphon cooling system with buffer tank is composed.

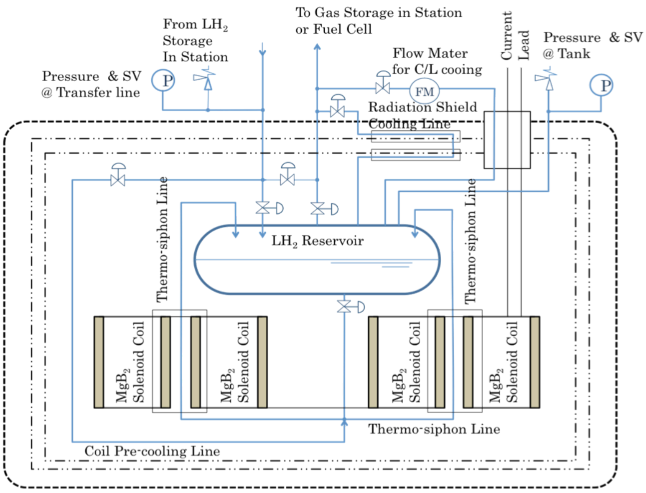

Fig. 10. Flow diagram in the SMES cryostat with thermo-siphon circulation.

the electrical lead lines have to be indirectly cooled across the electrical insulator. So, the coil cooling scheme by the thermo-siphon method is based on the design concept of the cryogen free magnets for particle detectors. Pure aluminum strips play a role of the thermal conductors for indirect cooling as shown in Fig. 6. The heat loads transferred from the coils are consumed as vaporization of liquid hydrogen. The liquid hydrogen is fed from the bottom of the reservoir tank and returned to its top gaseous region in the form of the thermo-siphon concept. The schematic SMES system and the flow diagram of the thermo-siphon cooling system are shown in Figs. 7 and 8, respectively. As an example, the design parameters of the cryogenic system for the 2 T solenoid SMES are shown in Table III.

Table III. - Parameters of SMES coil cooling system for the 2 T solenoid SMES

Buffer tank:	
Tank capacity	3 m^3
Tank pressure	150 kPa
Thermo-siphon circulation cooling circuit:	
Pipe channel diameter	20 mm
Pipe length	20 m
Pressure head	1270 MPa
Flow rate per coil	0.53 g/s
Coil cooling:	
Cooling mode	Conduction from thermo siphon line
Thermal conductor	Pure aluminum strip

6. Conclusion

We propose the Advanced Superconducting Power Conditioning System (ASPCS) to compensate the fluctuations of renewable energy sources and to be their effective use. It becomes clear that the moderate fluctuations of wind or photovoltaic generations can be compensated by the trend prediction method using the Kalman filtering algorithm. The SMES that is one of the key components of the system compensates the short-term fluctuations that cannot be compensated by the trend prediction. The design study of the SMES system is performed that the coil of 50 MJ is composed of four 10 MJ basic coils of the solenoid type fabricated with MgB_2 superconductors and also 100 MJ coil of the toroid type in case of the maximum magnetic fields of 2 T and 5 T. The 5 T coil is much more compact than the 2 T coil. For the safety, the coil is indirectly cooled at 20 K with liquid hydrogen by use of a thermo-siphon cooling system that had been developed for particle detectors.

In order to make the SMES system into economically practical use, the most important subject is to develop high performance MgB_2 conductors. It is expected to improve the characteristics of critical current up to around 5 T for more compact SMES coil systems.

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