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Design of Superconducting Magnets for a 600 kJ SMES

M. J. Park[a], S. Y. Kwak[b], S. W. Lee[a], W. S. Kim[a], S. Y. Hahn[c], K. D. Choi[d],
J. H. Han[d], J. K. Lee[e], H. K. Jung[b], K. C. Seong[f], S. Y. Hahn[a]
[a] *Korea Electrical Engineering & Science Research Institute*
[b] *Seoul National University*
[c] *MIT*
[d] *Korea Polytechnic University*
[e] *Woosuk University*
[f] *Korea Electrotechnology Research Institute*

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600 kJ SMES System의 초전도 마그넷 설계

박명진[a], 곽상엽[b], 이승욱[a], 김우석[a], 한승용[c], 최경달[d], 한진호[d],
이지광[e], 정현교[b], 성기철[f], 한송엽[a]

Abstract

The design of superconducting magnets for a 600 kJ SEMS was discussed. The basic constraint conditions in the design of a 600 kJ SMES magnet were V-I loss (< 1 W), inductance of magnet (< 24 H), the number of Double Pancake Coils (DPC, about 10), the number of turns of DPC (< 300), outer diameter of DPC (close to 800 mm) and total length of HTS wire in a DPC (< 500 m). As a result of optimum design, we obtained design parameters of the 600 kJ SMES magnet with two operating currents, 360 A and 370 A, which are in the limited conditions without V-I loss. V-I loss of each operating current was calculated with design parameters and V-I characteristic of the HTS wire. As a result of calculations, V-I losses with operating currents of 360 A and 370 A were 0.6 W and 1.86 W, respectively. Even though all design parameters of the SMES magnet in case of operating current of 360 A were in the restricted conditions, V-I loss of SMES magnet showed a tendency to generate at local DPCs, which are located on the top and the bottom of the SMES magnet more than that of the other DPCs.

Keywords : Critical current, HTS magnet, SMES , V-I loss

I. Introduction

The research of Superconducting Magnetic Energy Storage (SMES) system using High Temperature Superconducting (HTS) wire has actively progressed worldwide [1, 2]. HTS SMES design requires a power conversion, a cooling system and a design of magnet which is thought to be the core technology of the SMES system. Generally, it is known that HTS

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*Corresponding author. Fax : +82 31 496 8339
e-mail : pj1973@hanmail.net

wire does not generate the loss under DC current. But in increasing the current near the critical current, the voltage uprising from the HTS wire's power law relation and the heat generation are experienced. Thus high operating current end up with high heat generation and low operating current requires a big size magnet to keep demanded storage energy of a SMES system. In this paper, we carried out an optimum design of SMES magnet with several constraints without a limitation of *V-I* loss, and then we estimated *V-I* loss with design parameters of magnets.

II. Design of 600 kJ SEMS magnet

A. Performance of 4-ply HTS wire.

Basic work in design of HTS coils is to get characteristics of HTS wire such as critical current(I_c) – external magnetic flux density(B), index value(n) – temperature(T)-external magnetic flux density(B) and critical current(I_c)-temperature(T). In this research, a 4-ply HTS wire was used to design HTS coil for the 600 kJ SMES system. The 4-ply HTS wire is consisted of 2 HTS wires and 2 Brass tapes which is added on wide side of the HTS wire. Critical current and index value(n-value) of the 4-ply HTS wire are 274 A and 17 under 1 μ V/cm, at 77 K and self-field, respectively. Table 1 shows specifications of the 4-ply HTS wire.

In general, performance of a single HTS wire, such as critical current by external magnetic field and temperature, was reported under at 77 K and 300 *mT* in many other researches. However, characteristic data of multi-ply HTS wire under low temperature, high current and high magnetic field like 20 K, several hundreds ampere and several tesla are insufficient to design the SMES system. First of all, in this paper, we analyzed characteristics of 4-ply HTS wire such as B-I_c, I_c-T and n-value-T-B based on data of single HTS wire of reference [3]. Fig. 1 shows analyzed B-I_c curve of the 4-ply HTS wire at 20 K. B-I_c curve was analyzed by mapping digitized data of single HTS wire at 20 K in reference [3]. Fig. 2 shows measured critical current of 4-ply HTS wire at three points(B=3, 3.5 and 4) from a maker(AMSC) Analyzed I_c at perpendicular field of 3 T is about 468 A and accuracy of this value was 97.5 % compared to measured I_c from maker. So we used analyzed dada to design the 600 kJ SMES magnet.

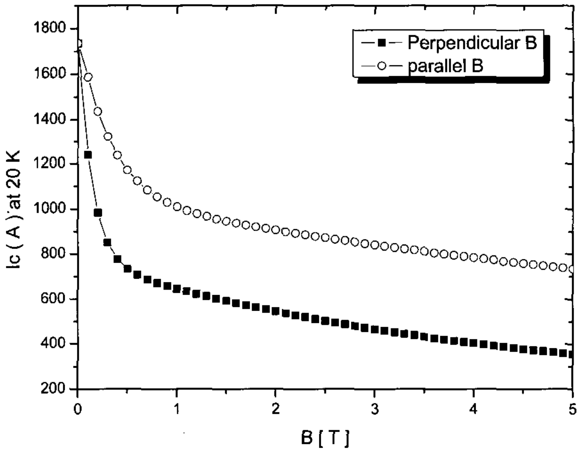


Fig. 1. Estimated B-I_c curve of the 4-ply HTS wire at 20 K.

Table 1. Specifications of 4-ply HTS wire.

Wire Property	Test Criteria	Measured Value
Max Width, Kapton Insulated	Continuous measurement entire length	4.5 mm
Critical current (Ic)	77 K, self-field, 1 μ V/cm	274 A
n-value of sample	77 K, self-field, 10^{-7} to 10^{-6} V/cm	17
Min. critical Tensile stress	At>95 % Ic retention(77K)	> 175 MPa
Reverse Bend Test(diameter)	> 95 % Ic retention	< 150 mm

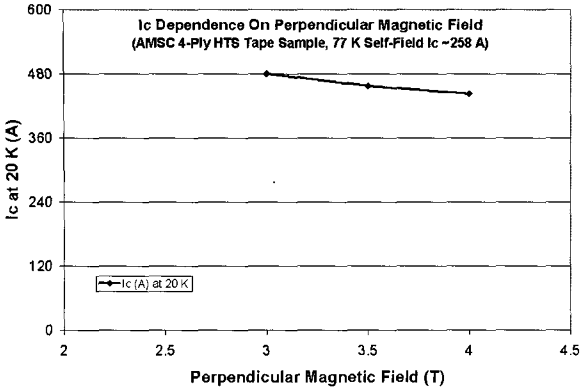


Fig. 2. Measured Ic dependence on perpendicular field at three points (B=3, 3.5 and 4 T).

B. Design constraints of 600 kJ SMES magnet

Fig. 3 shows the basic structure of the 600 kJ SMES magnet. The magnet is a single-pole solenoid type and consisted of double pancake coils (DPC). One DPC is also consisted of two single pancake coils (SPC). A bobbin to support HTS coil is made from copper and also acts as a cooling plate to cool down the HTS coil. G-FRP spacer of 1 mm thickness is located between SPCs for insulation. An operating temperature is 20 K, which is achieved by conduction cooling. Basic constrain conditions in the design of the 600 kJ SMES magnet are as follows.

1. Operating loss(V-I loss) : $< 1 W$
2. Inductance of magnet : $< 24\ H$
3. The number of DPC : about 10
4. The number of turns of DPC : < 300
5. Outer diameter of DPC : close to 800 mm
6. Total length of HTS wire in a DPC : < 500 m
7. Operating current can increase if result of design parameters is in condition 1-5.

The design of the 600 kJ SMES magnet was carried out by Auto-Tuning Niching Genetic Algorithm [4]. As a result, we obtained design parameters of two magnets. Table 2 shows specifications of magnets according to two operating current, 360A and 370 A, which are in the limited design conditions without V-I loss.

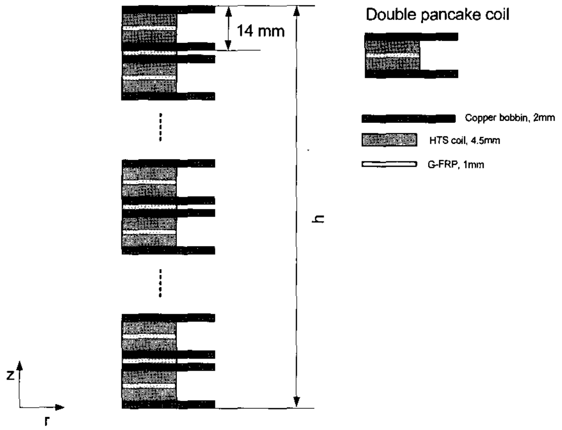


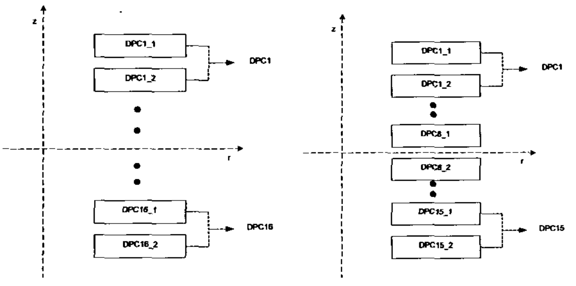
Fig. 3. DPC and the basic structure of magnet.

Table 2. The design parameters of the 600 kJ SMES magnet.

Model	Operating Current (A)	Number of turn of DPC	Number of DPC	Inner Diameter (mm)	Outer Diameter (mm)	Height (mm)
1	360	216	16	640	797.68	224
2	370	268	15	480	675.64	210
Model	Max. parallel field (T)	Max. perpendicular field (T)	Inductance of magnet (H)	HTS wire length of DPC (m)	Total wire length of magnet (km)	Storage energy (kJ)
1	3.84	2.87	9.66	487.8	7.8	626
2	4.95	3.23	9.19	486.5	7.3	629

C. *V-I* Loss of magnets

Fig. 4 shows a location of DPCs in two 600 kJ SMES magnets. DPC1 is placed the top of the magnet and consisted of DPC1_1 and DPC 1_2. In case of operating current of 360 A, total number of DPCs are 16. Since designed magnets are symmetric, results of all calculated data was represented about a half each magnet. Fig. 5 represented B-I_c curve of the 4-ply HTS wire at 20K and load-line of each DPC1_1 in the model 1 and 2 by perpendicular external magnet field. Current at a crossing of B-I_c curve and a load-line was determined as a critical current of DPC1_1 of each magnet. Critical current of each DPC1_1 in the model 1 and 2 by perpendicular external magnetic field are 439 A and 427 A, respectively.



(a) model 1 (b) model 2

Fig. 4. The location of DPC in the model 1 and 2.

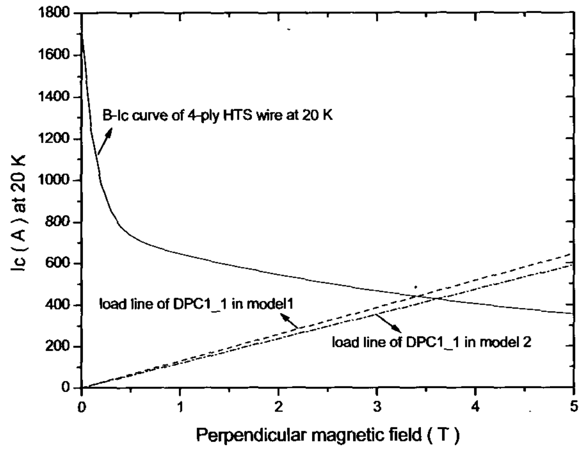


Fig. 5. B-I_c curve and load line of DPC1_1 (the model 1 and 2, perpendicular field).

Fig. 6 shows V-I curve of DPC 1_1 in the model 1 by following relation.

$$V = E_c\left(\frac{I}{I_c(B)}\right)^{n(B)} \times L \qquad (1)$$

where $E_c = 1\mu V/cm$, I is operating current, $n(B)$ = 20 for perpendicular field, 16 for parallel field, and L is the wire length of DPC1_1.

The dot line in Fig. 6 represents V-I curve by parallel field of DPC1_1 and did not take effect on whole V-I curve of DPC1_1 because it is very small compare to V-I curve by perpendicular field.

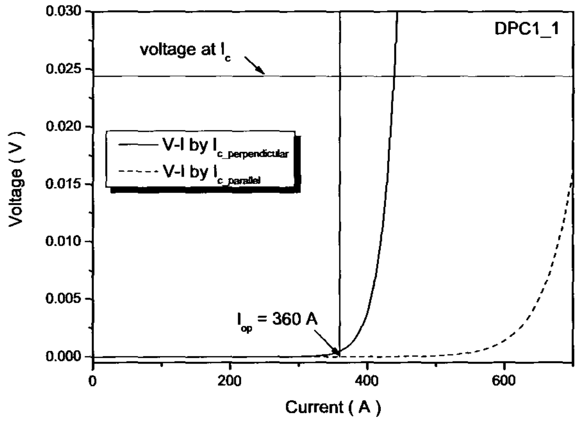


Fig. 6. V-I curve of DPC1_1 (the model 1).

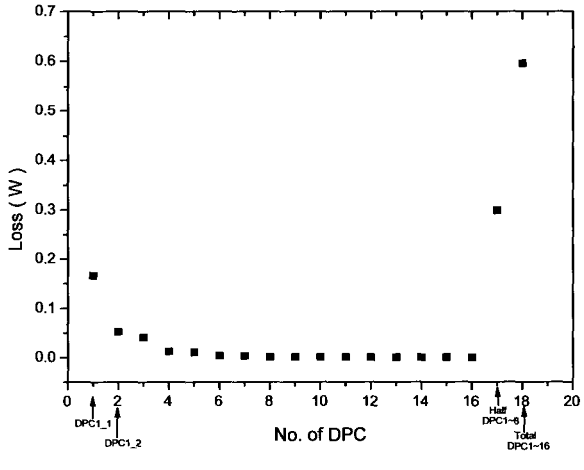


Fig. 7. V-I loss of each DPCs at operating current of 360 A (the model 1).

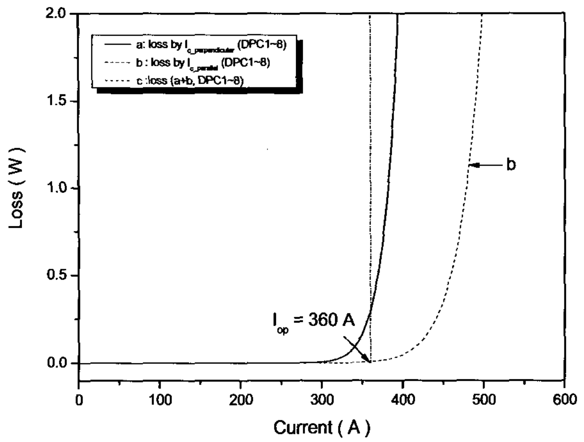


Fig. 8. *V-I* loss of the model 1 according to various currents.

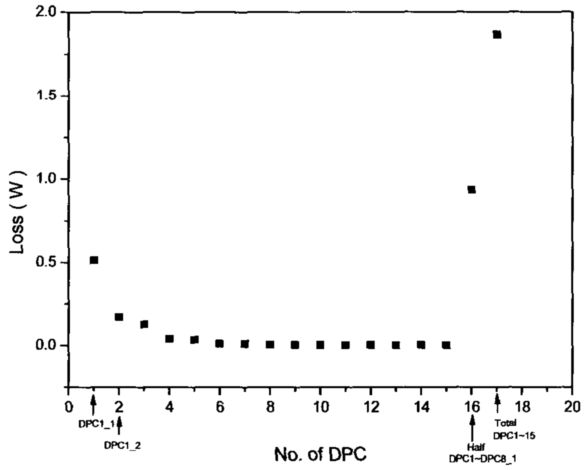


Fig. 9. *V-I* loss of each DPCs at operating current of 370 A (the model 2).

Fig. 7 shows *V-I* loss of each DPC in the model 1 at 360 A. Total *V-I* loss of the model 1 was about 0.6 *W*. This loss is in the restricted conditions.

Fig. 8 shows V-I losses according to various currents, which are the sum of DPC1 - DPC8. The dot line b in Fig. 8 and 10 represents *V-I* losses by parallel field and it was quite smaller than that by perpendicular field.

Fig. 9 shows *V-I* losses of each DPC in the model 2 at 370 A. Total *V-I* loss is about 1.86 *W*. This loss is in excess of the restricted loss condition for the design of the 600 kJ SMES magnet. Furthermore, loss of DPC1 and DPC15 which are placed the top and the bottom of the magnet is 1.026 *W*, and this is about 55% of total loss.

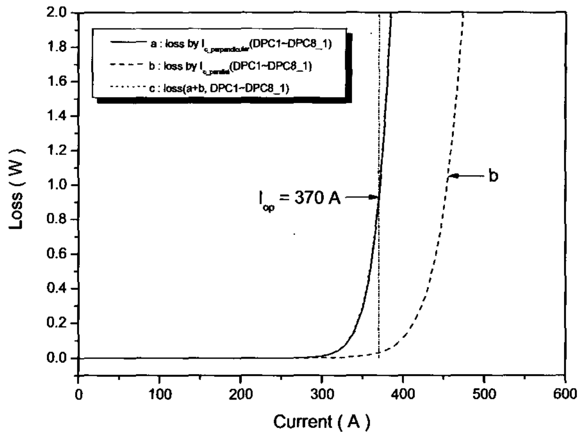


Fig. 10. *V-I* loss of model 2 according to various currents.

Fig. 10 shows *V-I* losses according to various currents of the model 2, which are the sum of DPC1 ~ DPC8_1.

III. Conclusion

The optimum design of the 600 kJ SMES magnet was carried out with several constraint conditions. For the optimum design, we obtained design parameters of the 600 kJ SMES magnet with two operating currents, 360 A and 370 A, which are in the limited conditions without *V-I* loss. *V-I* loss of each model was calculated with design parameters and *V-I* characteristic of the 4-ply HTS wire. As a result of calculations, *V-I* losses in operating currents of the model 1 and 2 were 0.6 *W* and 1.86 *W*, respectively. Even though all design parameters of the SMES magnet in the model 1 were in the restricted conditions, *V-I* loss of SMES magnet showed a tendency to generate at local DPCs, which are located the top and the bottom of the SMES magnet, more than that of the other DPCs. Therefore, additional researches are required to reduce that problem in the future.

Acknowledgments

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