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Conceptional Design of HTS Magnets for 600 kJ Class SMES

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***Abstract*—Development of a 600 kJ class Superconducting Magnetic Energy Storage (SMES) system is being in progress by Korea Electrotechnology Research Institute(KERI). High tem- perature superconducting (HTS) wires are going to be used for the winding of the SMES system and the design of the HTS windings for the SMES system is presented in this paper. We considered BSCCO-2223 wire for the HTS windings and the operating temperature of the winding was decided to be 20 K which will be accomplished by conduction cooling method using cyro-coolers. Auto-Tuning Niching Genetic Algorithm was adopted for an optimization method of the HTS magnets in the SMES system. The objective function of the optimal process was minimizing total amount of the HTS wire. As a result, we obtained output parameters for optimization design of 600 kJ class SMES under several constrained conditions. These HTS windings are going to be applied to the SMES system whose purpose is stabilization of the power grid.**

***Index Terms*—Auto-Tuning Niching Genetic Algorithm, BSCCO-2223, HTS, SMES**

I. INTRODUCTION

The SMES system has been actively developed world widely because its benefits are lager then other energy storage systems not only as an energy storage systems' ones but also a real power control in power grid [1]. In a SMES system, electricity is stored by circulating current in a superconducting coil without any losses. Because no conversion of energy to other forms is involved in the storing process, its round-trip efficiency can be very high [2]. Moreover, it has semi- permanent lifetime and no environmental problems because it only needs coolants such as liquid nitrogen which is nonflammable, clean and recyclable gas to maintain its operating temperature.

The magnets for SMES system used to be based on LTS (Low Temperature Superconducting) material such as NbTi or Nb_3Sn so far. But the HTS magnets start to be adopted for SMES system in these days because the HTS wire such as BSCCO wire makes possible the operation at higher temperature, shows excellent performance under high magnetic field compared with that of LTS ones, and improves the stability of magnets.

A development of a 600 kJ class SMES system is in progress by KERI. HTS wires are going to be used for a magnet of the system and the design of the HTS magnet for the system is presented in this paper. We are considering 3-ply BSCCO-2223 wires for the conductor of the HTS magnet and the operating temperature of the HTS magnet was decided to be 20 K which would be accomplished by conducting cooling method using cryo-coolers. With conditions above, an optimal design of HTS magnet was done using the objective function of minimizing total required amount of the HTS wire. Among several results of optimization according to the operating currents, a suitable case was analyzed to verify the design specifications.

II. ALGORITHM OF OPTIMIZATION

A. Auto-Tuning Niching Genetic Algorithm

In the design of the magnets for SMES system, the object function calculation time takes most of computing time. So it is important to reduce the number of object function calls. To reduce the number of object function calls, the niching genetic algorithm combined with deterministic method (PSM) was proposed in this paper [3]. The pattern search method is a direct search method not using derivatives as a genetic algorithm and can be extended to a multivariable function. So, the pattern search method is combined with the niching genetic algorithm. Compared with simple restricted competition selection (RCS), the niching genetic algorithm combined with pattern search method can reduce the number of object function calls. But this method requires the predetermined population size and niche radii of design variables. It is difficult to obtain such parameters properly [4]-[7].

A novel genetic algorithm automatically determining the population size and niche radii is proposed in this paper It embodies clearing method, elitism, and a deterministic method.

The principle of the auto tuning niching genetic algorithm is illustrated in Fig. 1. If the current population consists of

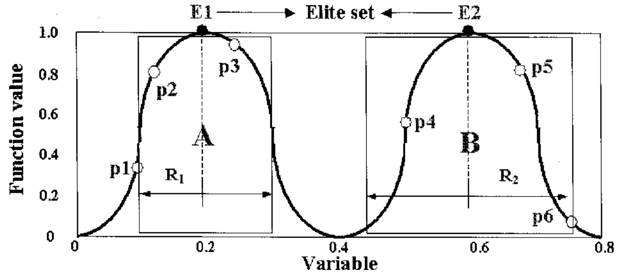

Fig. 1. Concept of proposed method.

p1–p6 as illustrated in Fig.1, p1–p3 are moved to E1 and p4-p6 to E2 by the pattern search method. Then, the elite set size becomes two (E1, E2) and the population size is automatically set to twice elite set size, that is four. The longest distance from E1 to each individual (p1-p3) becomes the niche radius (R_1) of E1. In the same way, the niche radius of E2 becomes R_2. In the next generation, the fitness of all individuals within the niche radii (R_1, R_2) of elite individuals is set to zero. If a new individual having nonzero fitness is moved to E1 by the pattern search method, the niche radius (R_1) of E1 is enlarged to the distance from E1 to that individual. That of E2 is changed in the same way. As the number of generations increase, the niche radii of elite individuals increase. If an individual moves to new peak, the elite set size is increased and the population size is automatically set to twice of elite set size.

The auto tuning niching genetic algorithm is consisted of 7 steps. A simple description of each step and the flowchart of the auto tuning niching genetic algorithm are shown in Table I and Fig.2, respectively.

B. *Verification of the Algorithm*

To evaluate the performance of the auto tuning niching genetic algorithm, the following test function that is shown in Fig. 3 is used. Total number of peaks of this function is 25.

$$F(x_1, x_2) = \sin(5\pi x_1) \times \sin(5\pi x_2), \quad 0 < x_1, x_2 < 1$$

TABLE I
DESCRIPTION OF EACH STEP IN AUTO TUNING NICHING GENETIC ALGORITHM

Step	Description
1	Initialization
2	Judgment of overlapping between population and elite population.
3	Peak search by pattern search method
4	Determination of elite population and niche radius
5	Determination and selection of next population
6	Reproduction by crossover and mutation.
7	Stop

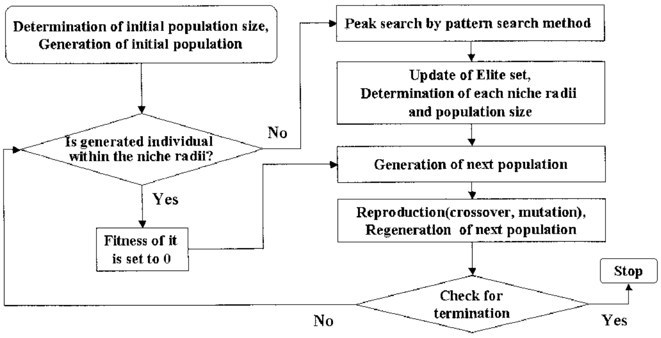

Fig. 2. Flowchart of the Auto-Tuning Niching Genetic Algorithm.

TABLE II
PERFORMANCE COMPARISON BETWEEN SIMPLE RCS AND NEW METHOD

	RCS	New Method
Iteration	77	23.12
No. of function evaluation	5775	2827
MPR	0.996	1

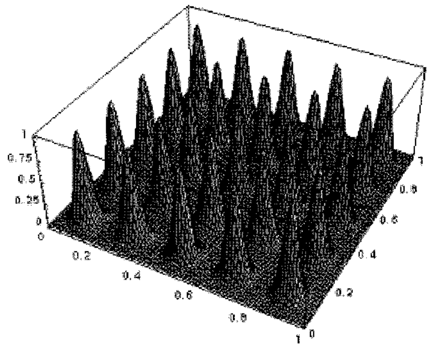

Fig. 3. Test function (2-dimensional sine function)

The results are summarized in Table II. It is shown that the proposed method can reduce the number of iteration and function evaluations compared with conventional niching genetic algorithm.

III. OPTIMAL DESIGN OF HTS MAGNET FOR SMES

A. *HTS Conductor and Design considerations*

In General, there are three types of coil for SMES – solenoid, multiple solenoid, and toroid. Solenoid type coils are simple to design and easy to manufacture, but they cannot prohibit or confine stray fields. Multiple solenoid coils show very good characteristics on stray field, but it has very poor energy density. Toroid-type can be a compromise proposal. A perfect toroid coil makes no stray field. The field is confined inside the coil, but it is very hard to realize such kind of coil. Instead, coils wound in pancake or stacked pancake coils can be configured to simulate similar effect. Meanwhile, toroid coils require more wire than solenoid coils but less wire than multiple solenoid coils [8]-[11]. In this research, the modular single-pole double pancake coil (DPC) type was selected in consideration of its installation environment.

The main objective of this study is to find optimal dimensions of SMES that can store 600 kJ of magnetic energy with minimum conductor length. There are several constraints to be considered for the SMES design process such as stray magnetic field, critical magnetic field, total superconductor wire length and geometrical constraints for supporting and cooling equipments. Among them, the total superconductor wire length is the most important factor when HTS wire is used. Hence, the length of HTS wire was selected as the main objective function. In consideration of potential cost for power electronics, the operating current was determined from 360 A to 420 A.

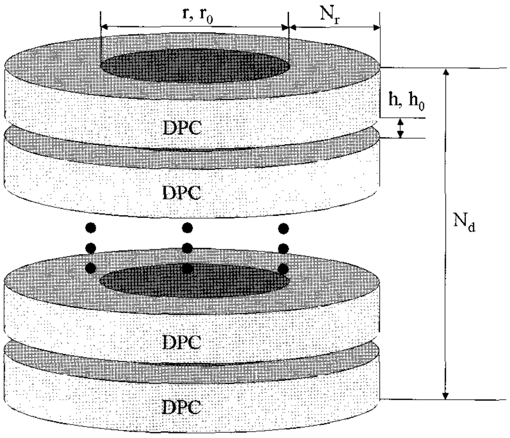

Fig. 4. Configuration drawing of the HTS magnet for SMES system design.

TABLE III
DESIGN SPECIFICATIONS OF HTS MAGNET FOR SMES SYSTEM

Configuration of magnet	Single-pole Solenoid with HTS double pancakes
HTS conductor	3-ply BSCCO-2223 wire
Operating current	360 ~ 420 A
Length of HTS wire in piece	470 ~ 490 m
Gap between double pancakes	4 ~ 10 mm
Inner diameter of magnet	300 ~ 500 mm
Stored magnetic energy	620 ~ 640 kJ
Constraint of B field	Perpendicular: 3 T Parallel: 6 T
Operating Temperature	20 K

The design parameters were considered as shown in Fig. 4. The minimum inner radius of single DPC module (r_0) is 300 mm and the minimum gap between two double pancake coils (h_0) is 4mm in consideration of insulator thickness. The length of HTS wire (L_0) per DCP module is 470 ~ 490 m and the constraint of storage energy of SEMS is 620 ~ 640 kJ. Also, the number of double pancake coil (N_d) and the number of winding turns (N_r) were considered as design parameters. Because the thickness of a HTS tape (rectangular cross-section) is a constant value of 1.2 mm, outer radius of a module can be evaluated simply using the number of turns. The constrained parallel and perpendicular flux density of SMES are under 6 T and 3 T, respectively. The detail design specifications and the constraint conditions are defined in Table III.

B. *Optimization process and Results*

To design the 600 kJ class SMES with the specifications and constraint conditions above, we had following 6 steps.

Step 1 - determine HTS tape and input operating current.

Step 2 - determine minimum inner radius of DPC, length of HTS tape per DPC module and minimum gap between DPC with considering insulator thickness of pancake coil as shape limitation conditions. In this step, also determine demanded storage energy of SMES and maximum parallel and perpen- dicular magnetic field as characteristic limitation conditions.

Step 3 - initialize and determine restriction range of design parameters such as inner radius of DPC, the number of turns, number of layer of total DPC and gap between DCP.

Step 4 - determine object function. In this work, we perfor- med optimization design on purpose to minimize total length of HTS tape in SEMS.

Step 5 - perform a processing of optimization by the auto- tunning niching algorithm.

Step 6 - obtain optimal design parameters of SMES and calculate storage energy, inductance and magnetic field of each DCP, parallel, perpendicular.

If design variables are given from the auto tuning niching genetic algorithm, 2-D axis-symmetric finite element analysis generates suitable meshes, from which objective function and constraints are calculated. The optimization process stopped when the number of generation decreased below the termination conditions.

Fig. 5 shows the flowchart SMES optimization process based on above 6 steps. The operating current and ranges of design variables were determined in initialization stage in Fig. 5. The optimization process is performed at each operating current value and each module was composed of stacked double- pancake coils. Table IV shows optimized variables in the ranges of each given operating current.

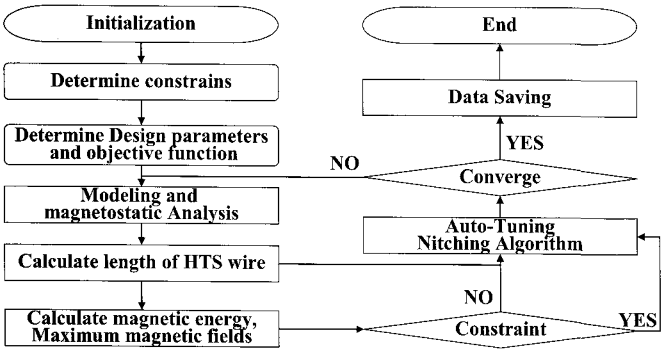

Fig. 5. Total SMES optimization process.

TABLE IV
OPTIMAL DESIGN RESULTS ACCORDING TO THE OPERATING CURRENTS

Design No.	1	2	3	4	5	6
Current [A]	360	370	380	390	400	420
Inner Dia. [mm]	320	310	300	320	300	300
Outer Dia. [mm]	682	682	674	688	676	676
No. of turns	151	155	156	153	157	157
No. of DPCs	17	16	16	15	15	14
Gap between DPC [mm]	4	4	5	4	5	5
Height [mm]	207	194	209	182	196	183
B in parallel [T]	5.6	5.7	5.7	5.7	5.87	5.88
B in perpendicular [T]	2.8	2.9	2.8	2.95	2.88	2.93
Stored energy [kJ]	637	625	627	627	635	626
Inductance [H]	9.83	9.13	8.68	8.24	7.93	7.1
Length of HTS wire [km]	8.1	7.7	7.6	7.3	7.2	6.7

The optimized quantities were verified using 3-D FEM. In case of design No. 3 in Table IV, the stored energy calculated by FEM was 628.6 kJ, which agreed well with the optimized result. Parallel and perpendicular magnetic field distributions of HTS magnet for design No. 3 obtained from FEM calculation, which also coincided well with the predicted values.

IV. CONCLUSION

The development of a 600 kJ class SMES system is in progress by KERI in Korea. 3-ply BSCCO-2223 wires are going to be adopted as the conductor for the SMES magnets. Several design results of HTS magnets for 600 kJ class SMES system under constrained conditions were presented in this paper. We used the Auto-Tuning Niching Genetic Algorithm for the optimiza- tion for the design parameters of the HTS magnet, and the objective function was minimizing total required amount of the HTS wire. Among several results of optimization, a suitable case was analyzed to verify the design specifications. In the future, we are going to estimate AC loss of SMES during discharge period for the detail design of the cryogenic.

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