Shape optimization of HTS magnets using hybrid genetic algorithms

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Two kinds of optimal methods and test of their abilities for searching optimal solutions are presented in the paper. A 12 T high temperature superconducting (HTS) magnet by Bi-2223/Ag tape is designed according to the methods. A new configuration of the HTS magnet which can reduce the winding volume and improve the efficiency of superconductor utilization effectively is suggested with consideration of the constraints, such as central magnetic filed, field homogeneity, critical current characteristic and so on.

INTRODUCTION

Bi-2223/Ag tapes are extensively used in HTS engineering field such as HTS magnets. The J_c-B characteristics of Bi-2223/Ag tapes hardly decrease at all in 20~30 K under high magnetic field and HTS magnets can set the operating temperature within a wide range. However, the properties of the Bi-2223/Ag tapes have an anisotropy in the critical current versus applied external magnetic field characteristic.

In Figure 1, the critical currents versus the magnetic flux density which was measured against the flux angle of 0-90^0 are shown for a Bi-2223/Ag tape at liquid nitrogen temperature. A critical current I_c was specified by the measured current-voltage characteristics of the tape, where I_c was defined by 1 μv/cm. The critical current is the lowest at 90 degree from Figure 1. It is necessary to consider the anisotropic B-I characteristic of Bi-2223/Ag tapes at the design stage. As the perpendicular component of the external magnetic field increases, the critical current is reduced largely. In the case of the HTS magnet with rectangular cross sectional shape, due to the higher radial magnetic field (the perpendicular component of magnetic flux density on HTS tapes) near the end of the coil, a large amount of superconductor is underused and only the terminal part of the coil works near the tape critical conditions. This lack of efficiency calls for a more thorough optimization of the magnet design, able to reduce the amount (volume) of superconductor while achieving the same performance. In this paper, we propose two kinds of optimal design methods for HTS magnets with consideration of the constraints, such as central magnetic filed, field homogeneity, B-I characteristic and so on.

OPTIMIZTION METHODS

The Genetic Algorithm (GA) is to mimic some of the processes observed in natural evolution. It can escape from local minima and deal with constrained nonlinear optimization problems. However, the solution obtained by GA is generally near the global minimum in the whole solution region. GA can easily appear premature at early iterations and evolution stalling at late iterations. It blocks seriously the GA to find the global optimum, so we adopt a fitness scaling technique which is from the simulated annealing (SA) method. The modified GA is named of GASA. Sequential Quadratic Programming (SQP) is an efficient method in finding local optima for constrained nonlinear optimization problems, but it can not guarantee that the solution is the global optimum for the problem. We combined GASA with SQP and it is called hybrid GA.

Figure 2 shows the flowchart of the first hybrid GA. The SQP is inserted in the GASA method as a local search operator to improve the local search ability. The method is called GASASQP.

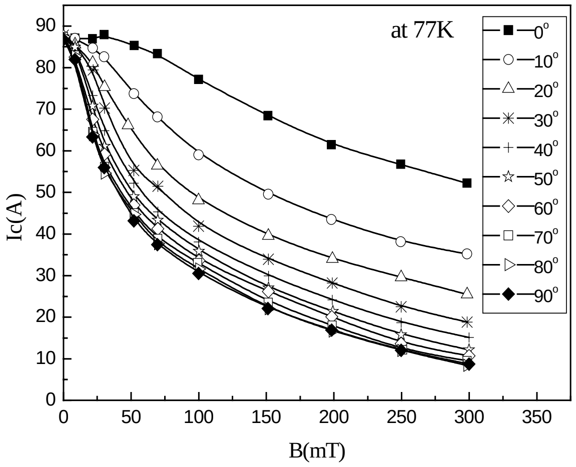

Figure 1 Critical current characteristics of the Bi-2223/Ag tape

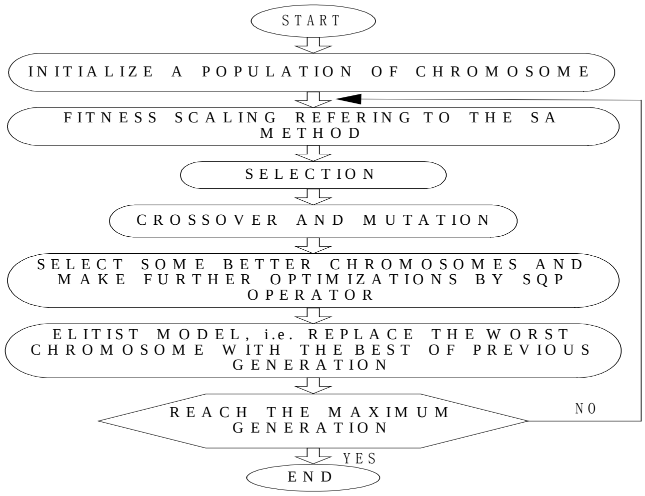

Figure 2 Flowchart of the first hybrid genetic algorithm (GASASQP)

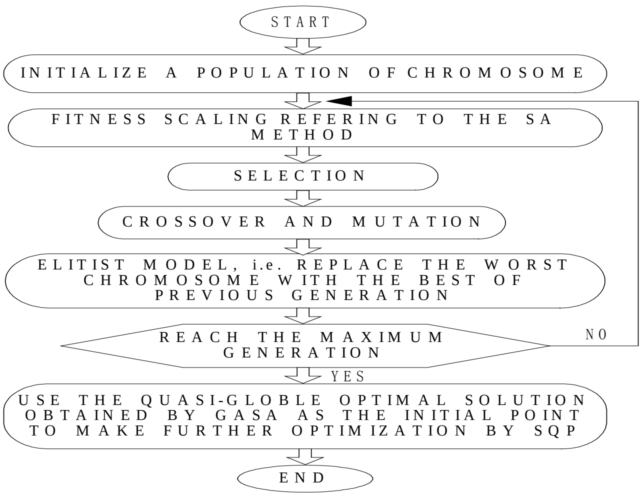

Figure 3 Flowchart of the second hybrid genetic algorithm (GASA+SQP)

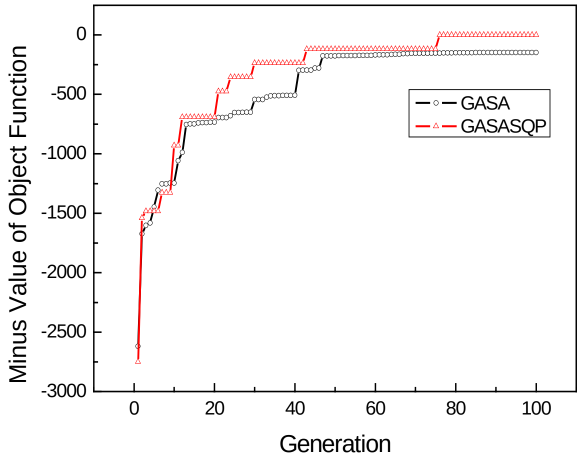

Figure 4 Comparison of optimum search abilities (Generation vs. Current Minus Value of Objective Function)

Talble 1 Comparision of the solutions

GA evolution generation / solution / optimal method	100	200
GASA	147.1185	0.4036
GASA+SQP	118.4385	1.2730e-4
GASASQP	1.2728e-4	——

Figure 3 shows the flowchart of the second hybrid GA. At the first, GASA searches the global optimum in the whole solution region to obtain a quasi-optimal solution, and then, the global optimal solution can be obtained by SQP. The method is named as GASA+SQP.

To contrast two kinds of methods, a function which is often used in optimization test is selected

[1]:

$$f(x) = 4189.829 - \sum_{i=1}^{10} (x_i \sin\sqrt{|x_i|}) \qquad x_i \in [-500,500] \tag{1}$$

The function has many local minima so that it is very difficult to obtain the global minimum value of zero. The solutions through the methods are listed in Table 1. It shows that the GASASQP has stronger searching ability from Table 1 and Figure 4, but it takes long time to obtain the optimal solutions.

EXAMPLE OF OPTIMAL DESIGN

A 12 T HTS magnet operating at 4.2 K with the field homogeneity of 1% in the radius of 20mm region, bore size of 100mm and Bi-2223/Ag tape with the size of 0.23 mm×3.5 mm is designed. Figure 5 shows the configurations of HTS magnets [2,3], where X_i (i = 1,….,6) are the length and the thickness of each coil, B_0 is the center magnetic flux density, and B_i (i =1,2) is the magnetic fields located at the radius of 20 mm.

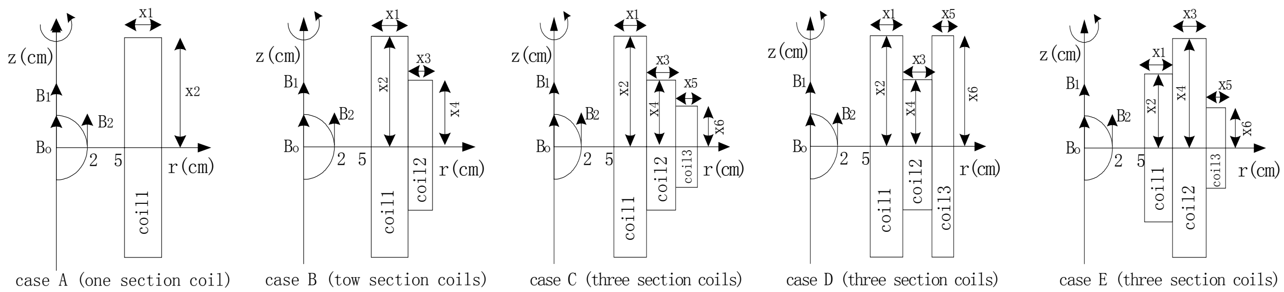

Figure 5 Models of superconducting magnets to be optimized

Minimize : V (the winding volumes of HTS magnets)

Subject to:

$$B_0 = 12 \text{ T} \tag{2}$$

$$I_{op} \le I_c(B) \tag{3}$$

$$I_c(B) \approx I_c(B_r) = 118 - 107\log_{10}(B_r) \tag{4}$$

$$\frac{|B_i - B_0|}{B_0} \times 100 \le 1.0 \qquad \text{(i=1,2)} \tag{5}$$

The constraints of B_o and the field homogeneity are represented by equations (2) and (5), respectively. The function of *B-I* characteristic for the HTS tape is approximately expressed as equation (4), where B_r is the radial magnetic field [4]. Equation (3) represents the constraint about the *B-I* characteristic of the tape, where I_{op} is the operating current.

Table 2 lists the optimal results and θ represents the angle between the z-axis and the magnetic flux density at the critical point. It should be noted that the length and thickness of each coil are discrete parameters given by the number of tape layers and turns, respectively. However, the discrete character of these parameters is neglected in our optimizations, so we select three better configurations (case A, case B, case E) from Table 2 based on the number of section coils and do some work on the length and thickness of each coil to determine the number of turns and layers. Table 3 shows the final results of optimizations of HTS magnets. And the values of winding volume in each design case are shown in Figure 6, the operating currents and maximum radial magnetic fields are shown in Figure 7.

The optimal results show that the winding volume of the HTS magnet can be reduced effectively and the maximum radial magnetic field decreases while the operating current increases by using the configuration in case E. The winding volume in case E is about 64.49% in case A, and the operating current in case E is about 30% higher than in case A.

Table 2 Optimal results of HTS magnets

	case A	case B	case C	case D	case E
$V(cm^3)$	49516.67	37913.36	33091.73	33566.94	31854.39
$I_{op}(A)$	57.70	68.11	74.99	75.42	74.73
$B_{r\max}(T)$	3.66	2.93	2.52	2.50	2.54
θ(deg)	50.78	69.84	64.54	46.10	21.30

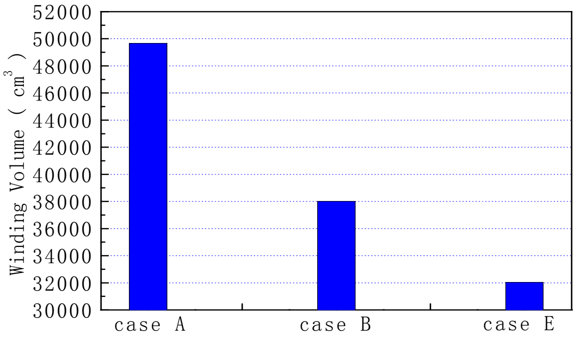

Figure 6 Winding volumes of the optimized HTS magnets

Table 3 Final optimal results of HTS magnets

	case A	case B	case E
$V(cm^3)$	49663.70	38019.57	32028.77
Thickness/turns per layer of coil1 (cm)	16.63/723	8.05/350	4.65/202
Length/layers of coil1 (cm)	35.70/102	50.40/144	30.80/88
Thickness/turns per layer of coil2 (cm)	——	6.37/277	4.32/188
Length/layers of coil2 (cm)	——	23.10/66	54.60/156
Thickness/turns per layer of coil3 (cm)	——	——	4.30/187
Length/layers of coil3 (cm)	——	——	18.20/52
$I_{op}(A)$	57.66	68.22	74.80
$B_{r\max}(T)$	3.66	2.91	2.53
θ(deg)	50.77	48.13	55.17
$B_{r\max}$ position (r, z) (cm)	(14.04, 17.85)	(9.42, 25.20)	(11.67, 27.30)
Calculating Time (minute)	3.50	5.20	24.80

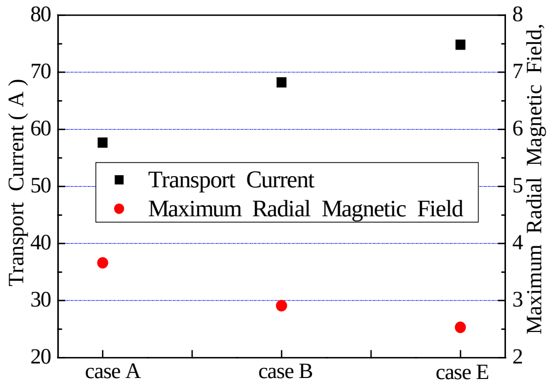

Figure 7 Operating currents and maximum radial magnetic fields of the optimized HTS magnets

CONCLUSIONS

Two kinds of optimal design methods for HTS magnets is proposed. As an example, a 12 T HTS magnet wound with Bi-2223/Ag tapes was designed. A new configuration of HTS magnet (case E) that can reduce the winding volume effectively is found. By using optimal methods, the efficiency of superconductor utilization can be improved, the amount of superconductor needed in the magnet and the electrical power wasted in refrigeration can be saved.

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