The Optimal Parameters Design of HTS-SMES Magnets

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ABSTRACT：In order to minimize the volume of HTS magnets and reduce the perpendicular component of magnetic field, two optimal algorithms-- iterative algorithm and genetic algorithm are presented to make optimal design of geometry parameter of HTS magnets. The example of optimal design of 500kJ HTS magnet is also given. And the comparison between iterative algorithm and genetic algorithm has done. The iterative algorithm is a optimal method which magnet performance varies with numbers of solenoid coil layer. The magnet geometry parameters should be determined with a rule of heightening the magnet performances and the minimum of magnet volume is found. The improved GA is applied well in magnet optimal design combining Britaina Sheffield University GA toolbox and the optimal results are obtained.

Keywords: HTS magnets，optimal design, minimum of volume, iterative algorithm, genetic algorithm(GA)

Ⅰ INTRODUCTION

Currently, large-scale application of high-temperature superconducting technology is in the research and development stage. To meet the demands of economic development and production of electrical systems, people begin to use high-temperature superconducting technology for energy storage system. SMES application consists of two parts: One is the large power system load regulation. Its purpose is to settle the grid voltage fluctuation, frequency fluctuations and other issues, thereby enhancing the stability of circuits; Second, we should improve local voltage fluctuation, and to protect lines from the impact of sudden failure.

Superconducting magnets is the core component of SMES. They mainly consist of two types -- helical (screw single solenoid and portfolio management) and the ring. Small SMES magnets are mostly solenoid magnet. Single solenoid superconducting magnet has advantages such as simple structure, high efficiency of energy storage and high utilization rate of material, etc.

At present, the price of superconducting materials is very expensive, reducing the size of magnets can reduce the amount of superconducting materials. Magnet thereby reducing the manufacturing costs[1]; The power consumed by the cooling of superconducting magnets is proportional to the volume of magnet. Therefore, reducing the size of superconducting magnets can reduce operating costs.

According to the principle of minimum volume of SMES geometric design parameters, reducing the size of high-temperature superconducting magnets with important economic significance. It is of vital economic significance to design geometric parameters of SMES magnet with volume minimum principles.

In the superconducting state high-temperature superconductors are anisotropic. Because its radial magnetic field (perpendicular to the surface of the magnetic material) has much more affect on the critical current than the axial one has(parallel to the surface of the magnetic material), the radial magnetic field effects is mainly taken into account in the optimization design of HTS Magnets.

In sum, high-temperature superconducting magnet design optimization of geometrical parameters to be met the energy levels and the current (magnetic field) requirements, is a multi - variable nonlinear constrained optimization problem. This is of practical significance and project reference value to the study and exploration. In this paper we study the design of a single-magnet solenoid coil, aiming at the minimization of the volume and the reduction of the radial magnetic field. The iterative algorithms and genetic algorithms are used to optimize the design of geometric parameters of high-temperature superconducting magnets. The corresponding optimal design of 500kJ energy magnets and a comparative analysis of two algorithms are given.

Ⅱ THE SUPERCONDUCTING MAGNETIC ENERGY STORAGE OPEIMIZATION BASED ON ITERATIVE ALGORITHM

Figure 1 shows a single-magnet solenoid coil structure, which, Ro solenoid coil outside diameter, inside diameter Ri, with a total length of 2 h, said solenoid coil floors N1, N2, said the typical coil turns.

Winding of inductor L through the current I, for its electromagnetic is

$$E = LI^2 / 2 \tag{1}$$

In principle, knowing the induction of the winding of certain size and the current, we will obtain the energy. On the superconducting magnet, the current work is related to the largest field of coil winding share space. So eventually coil winding inductance and current are the function of shape, size and other parameters of the winding.

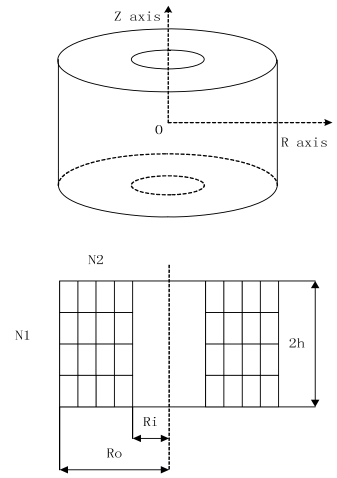

Fig.1. Single solenoid coils and Section maps

Supposed that parameters of the selected high-temperature superconductive as follows: S0—the cross sectional area (cross section in a wide b), E---HTS-magnet energy storage, λ ---magnetic filling factor. Parameters for the calculation of the magnetic coil are inductance L, Volume V coil and coil geometry (Ro, Ri, 2h, radial thickness c, the total turns N).

Iterative algorithm is a magnet parameter optimization method which is based on that Magnets parameters Changes With the rise of single-solenoid coil numbers. Under the premise of the Magnets parameters meeting the design requirements, the minimum sizes of superconductor material are found.

Iterative algorithm can be used to optimize the HTS-Magnets design of the following steps.

a) Calculation of coil inductance L

Known reserves of energy E, predict the current operation I, inductance L value obtained from (1).

b) Solenoid coil geometry calculation

Predicted radial thickness

$$c = R_o - R_i \tag{2}$$

Turns every level

$$N_2 = c / b = (R_o - R_i) / b \tag{3}$$

N1given rise of solenoid coils, axial length

$$2h = N_1 a / \lambda \tag{4}$$

$$N = N_1 \times N_2 \tag{5}$$

Inductance calculated by the formula[2]

$$L = \frac{6.4\mu_0 N^2 (2R_o)^2}{3.5\times(2R_o) + 8\times(2h)} \cdot \times \frac{2R_o - 2.25(R_o - R_i)}{2R_o} \tag{6}$$

Ro can be obtained , then Ri can be calculated: .Ri=Ro-c

c) Calculation of coil volume V

$$V = 2\pi\left(R_o^{\,2} - R_i^{\,2}\right)\times h \tag{7}$$

d) Calculated radial field

radial magnetic formula of Single solenoid magnet[3]

$$\begin{aligned} &B_r(R_i, c, h, r, z) \\ &= -\frac{\mu_0 J}{2\pi}[IN(R_i + c, -h; r, z) \\ &- IN(R_i, -h; r, z) - IN(R_i + c, h; r, z) \\ &+ IN(R_i, h; r, z)] \end{aligned} \tag{8}$$

$$IN(m, n; r, z) = \int_0^{\pi} \cos\beta\left(\sqrt{\xi^2 + Q^2} + U \ln\left[\xi + \sqrt{\xi^2 + Q^2}\right]\right) d\beta \tag{9}$$

$$\xi = m - r\cos\beta \tag{10}$$

$$Q^2 = r^2 \sin^2\beta + (n - z)^2 \tag{11}$$

$$U = r\cos\beta \tag{12}$$

Where z and r representatives seeking the axial and radial magnetic field position. Through the preparation of the end (that is, type (8) z=h) Br Poles seeking, the procedure can be obtained quickly Brmax.

e) Constraints field test

Figure 2 gives the magnetic-field component of the critical current curve (Ic--Bc curve) a temperature of 20K at the direction perpendicular to the surface of high-temperature superconducting wire. The curve indicated that the allowed current values under the maximum field to meet the demand constraints I<Ic (Brmax). If not satisfied with this, change the estimated current value I or the radial thickness coil c, from the first step to re-up to meet the conditions.

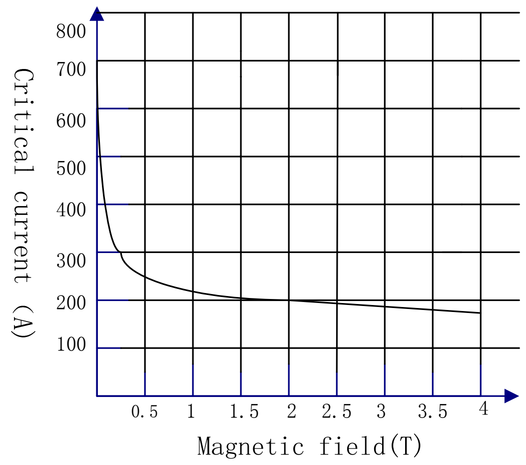

Fig.2. Ic-Bc curve of Super Conductor

f) Volume Optimization

Current I, the radial thickness of coil c are known constant and coil floors N1 is known variables. Coil volume V seeking to meet the minimum requirements to verify I<Ic (Brmax).

Ⅲ THE OPTIMAL DESIGN EXAMPLES OF 500KJ SMES MAGNETS BASED ON INTERATIVE ALGORITHM

Single solenoid geometrical parameters of 500kJ HTS Magnets design according to the principle of minimum volume. This is the optimal design of multi - variable nonlinear constrained optimization problem. The objective function is the volume of wire used which contain three variables of magnet coil diameter, the axial length and diameter.

$$\min V = 2\pi\left(R_o^{\,2} - R_i^{\,2}\right)\times h \tag{12}$$

Constraints conditions for the binding energy and the (magnetic) qualification :

1) energy storage is E 2) HTS magnet working current is less than the critical current.

HTS wire is high-intensity Bi-2223 material produced by the United States ASC. Its main characteristics are : silver jacket; The critical current at 77K Ic=115A;Strip a=4.1mm section size, b=0.3mm, So=1.23mm2 sectional area. Filling factor λ=0.8.

Based on the foregoing iterative algorithm optimization, Table 1 shows the results of the three groups. Conclusions from the analysis: When the radial thickness of the solenoid coil and current operations remain unchanged, with the rise of the coil, wire coil used in size to reach the minimum at turn rise N1=55. When the current operation I>160A, the smallest size made the biggest Brmax>3.5T. Constraints I<Ic (Brmax) dissatisfied; For each set of data in different operating currents, take the smallest wire size at maximum radial thickness of the corresponding magnetic field Brmax<3.5T.

Table 1: Three groups of optimal results

E(kJ)	*I*(A)	*c*(mm)	2*h*(mm)	*Ro*(mm)	*Ri*(mm)	N_1	*V*(dm^3)	B_{rmax}(T)
500	150	41	161.1	382	341	55	30.009	3.52
500	155	37	161.1	414	377	55	29.588	3.43
500	160	36	161.1	411	375	55	28.602	3.48

Given three groups of optimal curve under the optimization of the data presented, as shown in figure 3, the lowest point is the optimal result.

Iterative data use Microsoft Excel worksheet (including the integral calculation of the magnetic field using Matlab programming). The calculation is more burdensome, but achieving more accurate results in detail.

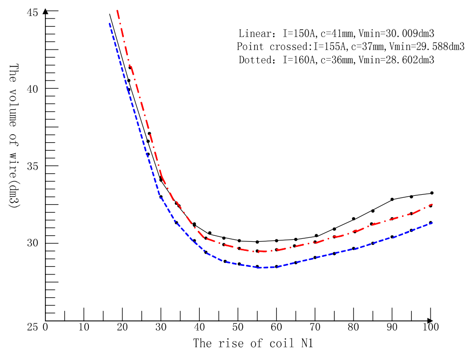

Fig.3. SMES Optimization 500kJ volume curve

Ⅳ SMES MAGNETS OPTIMIZATION BASED ON GENETIC ALGORITHM

Genetic algorithm is an effective way to solve optimization problems with strong global search ability but relatively weak local search ability. To improve the genetic algorithm optimization capabilities and taking into account the practical engineering magnet, this paper intends to improve the genetic algorithm from the aspects of the initial population, the objective function and constraints, the design of fitness function, genetic manipulation and termination of the main conditions. In addition, program employing related function in genetic algorithm toolbox to achieve good results in the application of optimization design of the magnet.

a) The creation of the initial population

In conventional genetic manipulation, the initial population is randomly generated. The impact of the initial population on the genetic algorithm implementation is significant.

In this paper crtrp function (creating real value initial population) is adopted. Chrom = crtrp (Nind, FieldDR) creats a real random matrix in size of Nind×Nvar with Nind as the number of individual stocks and Nvar number of variables for each individual.

b) The objective function and constraints

HTS magnet design is nonlinear constrained optimization problems while genetic algorithm optimization method is non-binding. The following bound issues need to be transformed to deal with in the application of genetic algorithms.

$$\begin{array}{lll} min & F(X_i) & x_1 \le X_i \le x_2 \\ s.t. & g_j(X) \ge 0 & (i = 1,2,...,m) \end{array} \tag{14}$$

X-type variables, X=(x1, x2,:,FIELD)

The paper applies penalty function to the transformation of (14) into unconstrained problems. To broaden its objective function:

$$P(X) = F(X) + \sum_{i=1}^{m} \left(\min(0, g_i(X))^2 \times R_i\right) \tag{15}$$

Among them, Ri, factor for punishment has different values, according to the nature of different constraint conditions.

Broadening the objective function (15) is a solution to minimizing the optimization problem. Usually, the maximum value of the objective function is desired in genetic manipulation, thus the function is defined as:

$$f(X) = - P(X) \tag{16}$$

c) Fitness function design

Fitness function known as evaluation function, which is designed by the objective function, serves as a standard to distinguish individual groups as well as the only basis for natural selection. Fitness function is always non-negative, under any circumstances, want value for the better. Whereas the objective function may be both positive and negative, and sometimes seek the maximum, and sometimes the minimum requirements. Consequently, there is a need to transform between fitness function and objective function.

Ranking function is employed to determine fitness value. FitnV = ranking(ObjV) is arranged according to the individual objective value objV in the order of their ranking from small to large, and return to a series of individual fitness value FitnV vector.

d) Genetic Manipulation

Genetic manipulation includes selection, crossover and mutation.

1) selection

Genetic algorithm choose to use opetators in the survival of the fittest operation for each individual: The individual with larger fitness value bears high probability of being passed on to the next generation whereas the individual with smaller value bears lower probability.

Genetic algorithm has created new genetic variation by means of individual crossover and mutation. With the evolutionary process more and more excellent individuals are produced. However, they also have the potential to destroy the best adaptable individual to the current group due to the operation rangdomness of crossover and mutation.

In this paper the optimal preservation strategy is used to evolutionize model in the survival of the fittest operation. That is, the current group of individuals with highest adaptbility do not involve in crossover and mutation operations. Rather, it replaces the individual with lowest adaptbility produced by the operation of crossover and mutation.

This step adopts selection function (senior selection function). NewChrom = select ('sus', OldChrom, FitnV, GAPP), use this function to choose fine individual from population Chrom and return it to new population SelCh. 'Sus' function is applied in ergodic random sampling to make individual choice for propagation probability. FitnV N is a series of vectors, including the fitness value of individuals in population Chrom; GGAP as generation gap parameters, indicates the population's probability of being copied. GGAP = 0.9 admission.

2) crossover

Crossover is to select two individuals from the group with a greater probability and exchange its certain space or spaces. In terms of genetic algorithms, crossover operation has a distinctive feature to distinguish from other evolutionary computation. It plays a key role in genetic algorithms, which is the main method of creating a new entity.

This step adopts recombine function (senior reorganization function). Recombin NewChrom = ('recdis' OldChrom. RecOpt) completed the reorganization of individual in stocks Chrom and freturn the new reorganized to Stocks NewChrom entity. Recdis function complet the discrete reorganization of a pair of individual in current stocks and return to new stocks after mating; RecOpt is an optional parameter which specifies crossover probability, RecOpt = 1.

3) mutation

The so-called mutation computation of genetic algorithm refers to it that the values of certain genes in the string of some individual chromosome are replaced by other allele genes, thus forming a new entity. In terms of the capacity of forming new entity through genetic algorithm, the mutation itself is a randomized algorithm, but with the combination of choice and crossover operator it can avoid the loss of information and then ensure the effectiveness of genetic algorithms.

This step adopts mutbgu function (advanced mutation function). NewChrom = mutate ('mutbga', OldChrom, FieldDR) implements individual mutation in the old population and returns the mutated individual to the new. Mutbga function uses designated probability to mutate each variable and returns to a new population.

FieldDR is a matrix, involving the boundary of each variable.

e) the Terminated conditions

Maximum evolution algebra is considered as a means to terminate conditions. In the course of optimization of the hign-temperature superconducting magnets, on behalf of more than 20 consecutive non-algebraic algorithm evolutionary changes, it is believed that this individual is the best or optimal solution which indicates the termination of genetic manipulation.

V BASED ON GENETIC ALGORITHM OPTIMIZATION EXAMPLES OF 500KJ SMES MAGNETS

Design geometric parameters of 500kJ single solenoid HTS magnet by the principle of minimal volume. This is the optimal design of multi-variable nonlinear constrained optimization problem. For the objective function is the size of wire used and the known single solenoid coil diameter, the axial length and diameter as variables of the objective function.

HTS magnet specifications:

Objective function: $V = 2\pi\left(R_o^{\ 2} - R_i^{\ 2}\right) \times h$

Known conditions: R_i =150mm；I=160A；E=500kJ；

Unknown conditions: 1)200mm ≤ R_o ≤ 3500mm；2)50mm ≤ h ≤ 400mm；3)$I < 0.6 I_c(B_{rmax})$;

N1 coil set to rise, N2 for the typical turns. The process of improved genetic algorithms is shown in figure 4, the involved basic formula is (1), (3), (4), (5), (6) and

$$I_c(B_{r\max}) = 118 - 107\log_{10}\left(B_{r\max}\right) \tag{17}$$

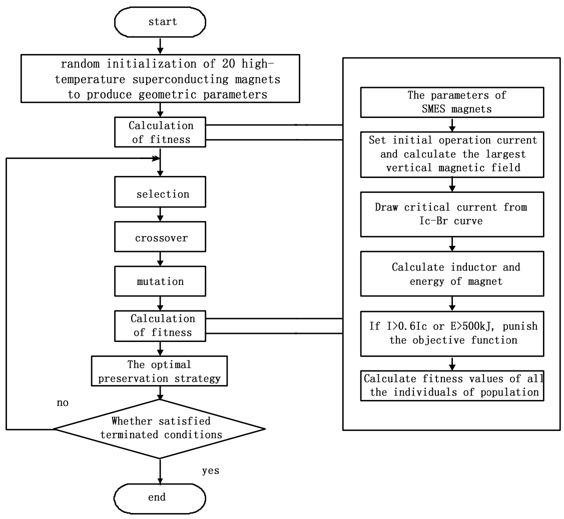

Fig.4. HTS magnet design optimization flowchart

The optimization design of 500kJ HTS magnet parameters based on genetic algorithm is carried out with Matlab software. Program in light of toolbox function and the results obtained are more accurate.

Figure 5 gives the optimal curve, results of the optimization are Ri = 150mm; Ro = 200mm; 2h = 233mm; N1 = 45; Vmin =12.8dm^3.

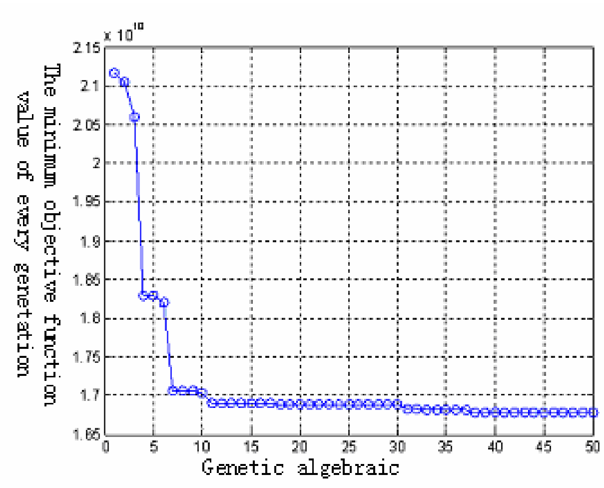

Fig.5. optimal curve

Ⅵ CONCLUSION

The critical work current in the HTS magnet is mainly constrained by the radial magnetic field component. It can be increased by reducing the radial magnetic field components perpendicular to the surface of the superconducting weight. In the paper, the optimization design of the geometric parameters of the superconducting magnet can be used to meet the minimum volume of superconducting wire and smaller radial magnetic field component.

The optimization design of SMES magnet in search of the minimum volume of wire is a multi-variable nonlinear constrained optimization problem. Constraints conditions are the binding energy and the (magnetic) qualification The iterative algorithm is used in the optimization of objective function. The data will be repeatedly incorporated into the formula and come to three groups of minimum size constraints, electrical and geometrical parameters of optimized magnet. Iterative data use Microsoft Excel worksheet (including the integral calculation of the magnetic field using Matlab programming), the calculation is more burdensome, but achieving more accurate results in detail.

Genetic algorithms are an effective way to solve optimization problem, which is characterized by its adaptability, robustness and global search capabilities. At the same time there exists weak local search capabilities and other issues. In this paper, regarding the practical issues in magnetic engineering, genetic algorithms have been improved, SMES magnet and its application to optimize design parameters have achieved good results. The optimal volume and the corresponding magnet geometric parameters are reached.

Compared with the iterative algorithm improved genetic algorithm eliminates a lot of intermediate derivation, data computation and statistical process and raise efficiency. The iterative algorithm design is a specific algorithm, while the improved genetic algorithm are more common in use, which provide template for such optimization problems.

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