MULTIOBJECTIVE OPTIMAL DESIGN OF SUPERCONDUCTING GENERATOR USING GENETIC ALGORITHM

Sang-Il Han, Itsuya Muta, Tsutomu Hoshino and Taketsune Nakamura

Department of Electrical Engineering, Graduate School of Engineering, Kyoto University
Yoshida-Honmachi, Sakyo-ward, Kyoto, Japan

ABSTRACT

A method for the design of superconducting generator using multiobjective optimization technique based on genetic algorithm is described in this paper. In consideration of electrical and mechanical characteristics of superconducting generator, efficiency and specific power of superconducting generator are optimized, respectively, and to find the best compromise solution between efficiency and specific power, multiobjective optimization is implemented. The results of the optimally designed superconducting generator show the reduction of dimension and loss, compared with those of 70MW class superconducting generator already developed in Japan, and therefore they demonstrate the effectiveness of the design method.

1. INTRODUCTION

Genetic algorithm(GA) and multiobjecive technique are used as a method for optimal design of superconducting generator(SCG) in this paper. Compared the conventional generator, the SCG has many merits such as high efficiency, compact volume, stability in power system and so forth. However, most studies on the SCG design have used the method of trial and error so far, and there are not any reports describing its optimal design[1]-[3].

The SCG treated in this work is designed as a model of 70MW class superconducting generator, which was developed in Japanese National Project(Super-GM) and successfully completed to verify electrical features in an electric power system. The results of optimally designed SCG are compared with those of the Super-GM.

Many works show that the GA is effective in the optimal design of electric machines and systems, and various methods of multiobjective optimization have been studied with new strategies of weighted sum approach and min-max approach[4]-[9]. Therefore, this work applies the GA to the optimal design for improving the efficiency and specific power of the SCG, and also utilizes the multiobjective technique for the optimization of two objectives, i.e. efficiency and specific power.

In the first step for the optimal design of the SCG, its efficiency and specific power are optimized, respectively. In the second step, to find the appropriate design data between those obtained by the efficiency and specific power optimization, the combination of two objectives made with the multiobjective technique of min-max approach is optimized. The design variables and constraints are chosen appropriately considering the electrical and mechanical characteristics of the SCG[1], respectively.

The design results of the SCG obtained throughout the optimal method in this paper show that the efficiency and specific power can be improved more, compared to those of the Super-GM.

2. OPTIMIZATION TECHNIQUE

2.1. Genetic algorithm(GA)

The GA is a global optimization method based on the machanics of natural evolution. To break through the difficulties that the deterministic methods have, the GA as an optimal method using stochastic techniques has been introduced. Many works show that the GA is well suited for a broad range of problems, and it is also considerably more efficient and provides relatively fast convergence less subject to be trapped in local optima. The GA starts with a population of randomly generated candidates and evolves towards the better solutions by using genetic operators such as crossover, mutation, selection and reproduction.

The coding technique of the GA is mainly classified three coding techniques such as binary representation, gray representation and real number representation known as float point representation. Like most applications of the GA to constrainted optimization problems, the real coding representation, which is encoded as a vector of real number to represent a solution, is used in this work.

As genetic operators, the crossover is applied by the direction-based crossover which uses the values of objective function in determining the direction of genetic search. The operator generates a single offspring x' from two parents x_1 and x_2 as follows[5]:

$$x' = r \cdot (x_2 - x_1) + x_2 \qquad (1)$$

where r is a random number between 0 and 1. It is assumed that the parent x_2 is not worse than x_1.

The process of mutation is impremented by the nonuniform mutation which is introduced for fine-tuning capabilities aimed at achieving high precision. For a given parent x, if its element x_k is selected, the offspring is $x' = [x_1, \cdots, x'_k, \cdots, x_n]$, where x'_k is randomly selected and made as follows[5]:

$$x'_k = x_k + (x_k^U - x_k) \cdot r \cdot \left(1 - \frac{t}{T}\right)^b$$

$$\text{or } x'_k = x_k + (x_k - x_k^L) \cdot r \cdot \left(1 - \frac{t}{T}\right)^b \qquad (2)$$

where x_k^U and x_k^L are the maximum and minimum of x_k, r is a random number from [0,1], t and T are the current and total generation number, and b is a parameter determining the degree of nonuniformity, respectively. In this paper, the number of population and generation are given by 100 and 30000, respectively. Crossover probability and mutation probability are also yield by 0.5 and 0.1, respectively.

2.2. Multiobjective optimization

2.2.1. General expression of multibojective problem

The general expression of multiobjective optimization can be written as

$$\min f(\mathbf{x}) = (f_1(\mathrm{x}), f_2(\mathrm{x}), \cdots, f_p(\mathrm{x})),\ \mathbf{x} \in X \qquad (3)$$

$$\text{s.t. } g_i(\mathbf{x}) \le 0,\ i = 1, 2, \cdots, m_1$$

$$h_j(\mathbf{x}) = 0,\ j = m_1 + 1, \cdots, m$$

where f , g_i and h_j are real valued functions, X is a searching space of these functions, and $\mathbf{x}$ is an n-dimensional real vector with components x_1, x_2, …, x_n and is a set of design variables in the optimal design problem. p is the number of objective and m is the number of constraint, respectively. The function $f(\mathbf{x})$ with p objectives is usually called a multiobjective function. $g_i(\mathbf{x}) \le 0$ and $h_j(\mathbf{x}) = 0$ are called inequality constraints and equality constraints, respectively.

2.2.2. Multiobjective technique

As the multiobjetive technique searching the global optimum in the multiobjective problems with more than two objective functions, weighted sum approach, ε-contraint method, min-max approach and so forth are used generally. In this paper, as a method to find the appropriate solution between two objectives, min-max approach, which can search the solution close to each objective, is applied.

In the min-max approach, an optimum of a multiobjective function gives the solution that treats all the objectives on terms of equal importance, and this method has the advantage of being very effective and easy to implement. When the ideal solutions of each objective function are determined, the min-max optimum gives the smallest values of the relative deviation of individual objective functions from their ideal solutions. The new combination function is defined by[6]

$$f(\mathbf{x}) = \min_{\mathbf{x} \in X_f} \max_{k \in K} \left\{ \frac{\left| f_k(\mathbf{x}) - f_k^* \right|}{\left| f_k^* \right|} \right\} \qquad (4)$$

where X_f is feasible region in decision space and f_k^* is ideal solution of kth objective.

3. SUPERCONDUCTING GENERATOR(SCG)

The SCG dealt with in this paper is the structure with superconductig coil in field winding of the rotor as shown in Fig. 1.

The rotor mainly consists of coil support cylinder, superconducting field coil, vessel and two dampers(cold damper and room temperature damper). As the means to intercept heat convection from the outside, there are vacuum spaces between the vessel and the cold damper, and between the cold damper and the room temperature damper. The superconducting field coils are made of NbTi coils and are arranged with CuNi to reduce the loss of the coils. Vessel is filled with the liquid helium coolant, which is supplied from the exterior of the rotor to the interior by its density difference and decompression process generated due to the difference of its centrifugal force and density.

The cold damper consists of a conductive part sandwiched with the damper supports. The cold damper

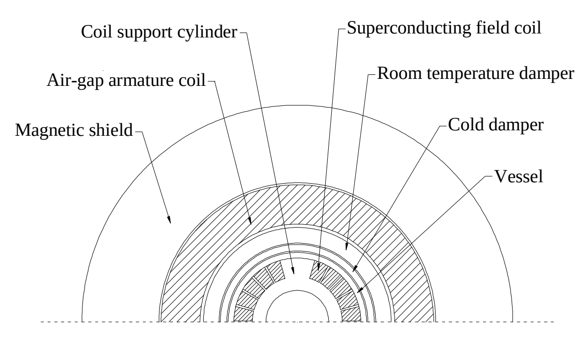

Fig.1. Cross-section structure of the SCG

blocks the radiation heat from the outside, and shields low-frequency asynchronous magnetic field generated from the armature coil in fault. The room temperature damper, which is comprised of a conductive part and a damper support, also restrains the mechanical rotor fluctuation and shields high-frquency asynchronous magnetic field.

The feature of the stator in the SCG is that the armature coil is the air-gap structure. Differently from the conventional manner in which the armature coil is inserted into the slots to endure large electromagnetic force, the SCG has the air-gap armature coil that is placed in FRP(Fiberglass reinforced plastic) with high strength. The armature coil is made of double transposed strand conductors and several water-cooling tubes.

The magnetic shield, which is placed in the exterior of the armature coil, forbids high magnetic field to be leaked to the outside, and in the design of the magnetic shield, it is necessary that the tangential flux density in the magnetic shield should not saturated[10].

4. APPICATION TO THE SCG DESIGN

The design for optimal efficiency and specific power of the SCG is described in this section. Several design variables are selected and some inequality constraints are given appropriately for three optimization problems, that is, loss, volume and combination of loss and volume.

4.1. Design variables and constraints

A set of seven design variables with the limited ranges is given as follows:

1. Mean radius of the superconducting field coil
2. Thickness of the superconducting field coil
3. Inner radius of the magnetic shield
4. Thickness of the armature coil
5. Air gap between the rotor and the stator
6. Thickness of support part of the room temperature damper
7. Thickness of support part of the cold damper

Taking into account of electrical and mechanical characteristics of the SCG, several constraints are defined as follows:

1. A deviation of two inner radii of the stator obtained from different equations ≤ 0.2%: one is given by the sum of outer radius of the rotor determined from the design of the rotor and air-gap between the rotor and the stator, and the other is given by design of the stator.
2. A deviation of two magnetomotive forces per one pole of the superconducting field coil obtained from different equations ≤ 1%: one is given by the design of field coil, and the other is induced from the relationship of magnetic flux density of the field coil and the magnetic shield.
3. An equivalent end length of the armature coil ≤ an allowable length determined by the rated specifications.
4. Magnetic flux density of the armature coil ≥ 1.1T.
5. Transient electromagnetic stress of the room temperature damper ≤ an allowable design stress 400MPa.
6. Transient electromagnetic stress of the cold damper ≤ an allowable design stress 160MPa.

4.2. Objective functions

The objective function, which contains the variables, is optimized during the optimization process. In this paper, the multiobjective design of the SCG is implemented.

First of all, single individual objective is optimized to obtain the maximum efficiency and specific power, respectively.

The optimization of efficiency can be obtained by minimizing the loss of the SCG. Total loss approximately consists of copper loss of the armature coil, iron loss of the magnetic shield, mechanical loss, stray load loss and eddy current loss of the armature coil. Hence, total loss can be expressed as follows;

$$P_l \cong 3R_a I_a^2 + \pi(2h_c r_c + r_c^2)\omega_i \eta \rho_c l_s + 8r_{ai} \times (l_s + 0.15) \times \left(\pi r_{ai} \times \frac{N_s}{60}\right)^2 + 0.4(3R_a I_a^2) + \frac{3}{4}\sigma_a \omega^2 B_a^2 N_a \frac{S_a^2}{\pi N_{as}} \times \left(24\sqrt{\frac{S_a}{\pi}}\right) \quad (5)$$

where R_a and I_a are resistance and current of the armature coil, and h_c and r_c are thickness and inner radius of the magnetic shield. ω_i, η, ρ_c and l_s are loss factor, space factor, specific gravity and length of the magnetic shield, respectively. r_{ai} is inner radius of the stator, N_s is synchronous speed of the rotor, and N_{as},

Table.1.Specifications of the SCG design model

Parameter	Unit	Value
Output power	MW	74.7
Number of pole		2
Power factor		0.9
Frequency	Hz	60
Synchronous speed	rpm	3600
Synchronous reactance(X_d)	p.u.	0.35
Current density of armature winding	A/cm^2	110
Current density of field winding	A/mm^2	60
Armature winding time constant(T_a)	sec	0.11
Transient time constant(T_{do}')	sec	260
Subtransient time constant(T_{do}'')	sec	1.1
Sub-subtransient time constant(T_{do}''')	sec	0.04

S_a , σ_a and B_a are the conductor number per a coil, cross-section area, conductivity and radial magnetic flux density of the armature coil, respectively.

Specific power of the SCG can be obtained by dividing its volume into its effective power, and therefore the maximum of specific power can be given by minimizing the volume, where the effective power is constant. The volume V can be expressed by

$$V = \frac{\pi D_s^2 L}{4} \tag{6}$$

where D_s is outer diameter of the magnetic shield, and L is length of the magnetic shield which is assumed to be equal to the length of effective straight part of the armature coil l_s [10].

Next, min-max approach is utilized to obtain the compromise solution between the optimal efficiency and specific power. The best trade-off design data of efficiency and specific power are obtained by giving the optima found by the optimization of individual objectives to the ideal solutions in min-max approach.

Table.2. Comparison of design parameters of the SCG obtained by different objective functions

Parameter	Unit	S	A	B	C
Transient reactance(x_d')	p.u.	0.25	0.279	0.278	0.278
Subtransient reactance(x_d'')	p.u.	0.21	0.242	0.241	0.241
Sub-subtransient reactance(x_d''')	p.u.	0.18	0.194	0.192	0.193
Magnetic flux density at the armature coil	T	1.1	1.1	1.1	1.1
Magnetic flux density at the inner surface of the magnetic shield	T	-	0.91	0.91	0.91
Outer diameter of the rotor	mm	880	848	842	844
Length of the magnetic shield	mm	1500	1300	1310	1307
Total loss	MW	1.411	1.262	1.273	1.265
Volume	M^3	-	4.129	4.076	4.096
Efficiency	%	98.15	98.34	98.32	98.33
Specific power	MW/ m^3	-	18.09	18.33	18.24

S: Super-GM Model developed in Japan (1999)[2]
A: Efficiency optimization
B: Specific power optimization
C: Multiobjective optimization by min-max approach

5. RESULTS AND DISCUSSIONS

Table 1 shows specifications for the optimal design of single objective and multiobjective of the SCG. Table 2 shows the design results obtained by the optimization of efficiency and specific power of the SCG and those of multiobjective optimization using min-max approach, respectively, compared with design results of Super-GM model.

As shown in Table.2, there is a little difference compared the design results obtained by the efficiency optimization with those by the specific power optimization. In addition, the results of multiobjective optimization give the trade-off values between the efficiency optimization and the specific power optimization. Consequently, it represents that the optimal design of the SCG using the GA and multiobjective technique can reduce its loss(about 1.265MW) and volume(about 4.096MW/m^3) compared with those of

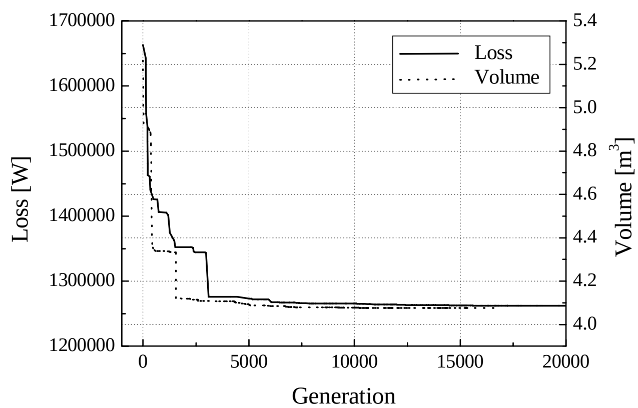

Fig. 2. Convergence of loss and volume in optimization process

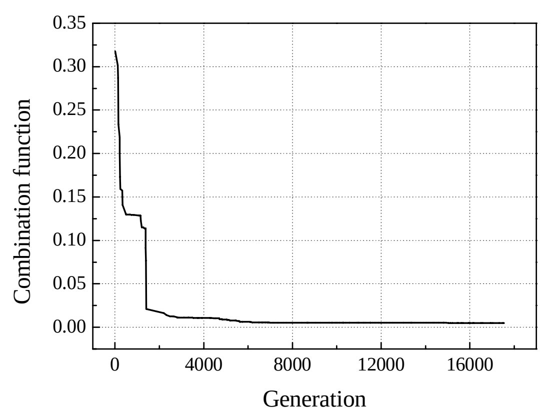

Fig. 3. Convergence of combination function made of loss and volume by min-max approach in optimization process

Super-GM model, and hence that the efficiency and compactness improvement of the machine is expected .

Fig. 2 displays the variation of loss and volume with the number of generation during the optimization process, and the convergence of combination function made of loss and volume by min- max approach to the number of generation is shown in Fig. 3.

6. CONCLUSIONS

The SCG with 3 phase, 2 pole, 74.7MW rating has been designed for the optimization of efficiency and specific power using an optimization technique of the GA, respectively, and also for the multiobjective optimization of efficiency and specific power using the GA and multiobjective technique of min-max approach. Compared the design results obtained by the efficiency optimization with those of the specific power optimization, there is a little difference. The best compromise solutions have been found applying the optima of two objectives to the ideal solutions in min-max approach. The results of the multiobjective optimization have the compromise values between those obtained by the optimization of individual objective.

In conclusion, the design results show that the dimension and loss of the SCG can be reduced, and accordingly more compact dimension and higher efficiency can be achieved, compared with those of the Super-GM model. After all, it could be confirmed that the design method used in this paper should be effective and aid the optimal design process of the SCG.

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