Optimization of design parameters of a toroid HTS coil for large scale SMES

Ji-Young Lee[1], Seyeon Lee[2], Kyeongdal Choi[2] and Woo-Seok Kim[2]

[1]Center for Axion and Precision Physics Research, Institute for Basic Science, Daejeon 34141, Korea
[2]Korea Polytechnic University, Gyeonggi-do 15073, Korea

Recent researches of large scale Superconducting Magnetic Energy Storage (SMES) have included a toroid type High Temperature Superconducting (HTS) coil to maximize the critical current density and the stored energy density eventually. However, the toroid type HTS coil is not only difficult to be realized but also to be analyzed because the symmetric structure of the toroid type coil causes very strong mechanical stress in the coil and require a 3-dimensional numerical calculation, such as finite element method (FEM). In this article, we suggest rapid computation method to acquire the maximum magnetic flux density applied perpendicularly to the surface of the 2G HTS conductor, the stored energy, and maximum hoop stress in the toroid coil. Although the result with this method includes some errors, we were able to reduce these errors to within 5 percent to get a reasonable estimation of the design parameters of the HTS toroid coil system. As a result, the calculation time by the suggested method could be reduced to 0.1 percent of the 3-dimensional numerical calculation. By using the suggested calculation, an optimal design process for a module SMES coil is in progress.

***Index Terms*— SMES, Toroid coil, Magnetic Field, Stored Energy, Mechanical Stress**

I. INTRODUCTION

SECOND generation high-temperature superconducting wire will be affected in significant ways by the magnetic flux density applied perpendicularly on the wide surface of the wire [1]. Because of this, when we design a High Temperature Superconducting (HTS) coil for the Superconducting Magnetic Energy Storage (SMES), the coil should be designed to have as small a perpendicular magnetic field as possible, so that its critical current can be maximized. In fact, most of the HTS coil for the SMES system adopts the toroidal shape to minimize the magnetic flux density applied perpendicularly to the wide surface of the HTS wire.

The magnetic field itself is not the only factor that affects the critical current of the HTS coil. A superconducting coil is usually operated in a high magnetic field and a cryogenic environment. This environment may cause very high mechanical stress and strain. This strain can not only decrease the structural stability of the system but also cause the degradation of the superconducting coil. When the phase transition occurs beyond this mechanical stress, especially hoop stress, the degradation of the critical current and critical magnetic field may cause a permanent damage that cannot be recovered. Therefore, the mechanical stress is also a part that should be reflected in the SMES design.

We usually use the finite element method (FEM) for the calculation of all the parameters and characteristics of the HTS coils. However, a toroid shape coil requires a 3-dimensional computation to acquire the characteristics of its critical current density–magnetic field relations, which needs very complicated numerical calculation, very high computer specification, and long calculation time [2]. Very long calculation time occasionally misleads design works, required several iterations thus leading to hasty conclusions.

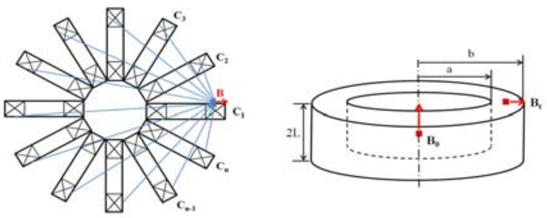
In this article, we propose a fast estimation method to obtain the perpendicular component of the magnetic flux density of the HTS toroidal coil and a maximum hoop stress, which affects critical current of the superconducting coil using the calculating method. In addition, we propose an effective calculation method to obtain the stored energy. In this study, we have achieved a significant reduction in the calculation time by using the suggested method for a fast design process.

II. CALCULATION METHOD

A. *Calculation of perpendicular field*

In order to realize a toroid type coil with HTS tape shaped wire, we generally arrange several numbers of Single pancake coil (SPC) as a toroidal type, which is shown in Fig.1 (a).

The point at which the maximum magnetic flux density occurs in the SPC is generally at the mid-point of each side of each SPC shown in Fig. 1 (b), which is the fact verified by the calculation result of the FEM analysis.



(a) (b)

Fig. 1. Toroid type HTS pancake coils for SMES; (a) the contributions of all other pancake coils to the same point of maximum radial field, (b) the point and self-field (B_t) of maximum radial magnetic flux density.

As a pre-calculation for an estimation of the self-field, the ratios of the central magnetic field and the maximum radial magnetic field as a function of the shape parameters of the single pancake coil were obtained according to most of possible combination of the shape parameters by using numerical computation [3].

Next, with the coordinates of the coil, the Biot-Savart Law, which determines the expression of the external magnetic field acting on the mid-point of one SPC resulting from the other SPCs.

B. Calculation of stored energy

We calculate the stored energy of an ideal toroid using the inductance. But the real toroid type coil has a gap between the SPC, as shown in Fig. 2. To correct this, we use the correction function reflected in the actual percentage of SPC as a parameter, θ_{ratio} . The new parameter, θ_{ratio} can be calculated as in (1). And the correction function was made at the rate of calculating the stored energy and using FEM.

$$\theta_{ratio} = \frac{\theta_{SPC}}{\theta_{SPC} + \theta_{gap}} \tag{1}$$

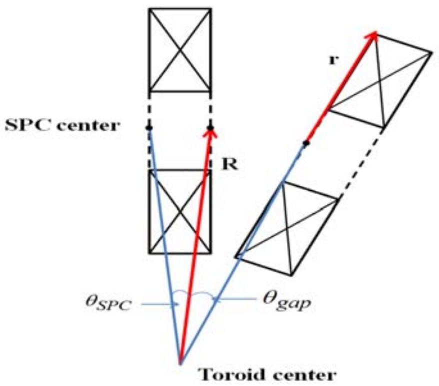


Fig. 2. Cross section showing a ratio of the SPC in the real toroid type coil.

C. Calculation of hoop stress

Generally, the maximum hoop stress in a regular solenoid coil appears at the innermost turns of the coil on the center plane, and can be calculated by (2) in general [4].

$$\sigma_{hoop} = \frac{\lambda J B_1 a_1}{\alpha - 1} \left\{ \begin{aligned} &(\alpha - \kappa)\left[\frac{2+\nu}{3}\left(\frac{2\alpha^2 + \alpha + 1}{\alpha + 1}\right) - \frac{1+2\nu}{3}\right] \\ &-(1-\kappa)\left[\frac{3+\nu}{8}\left(2\alpha^2 + 1\right) - \frac{1+3\nu}{8}\right] \end{aligned} \right\} \tag{2}$$

In case of the toroid type coil, the same equation can be applied to estimate the maximum hoop stress by obtaining the axial magnetic flux densities at the innermost and the outermost turns of the SPC coil, which can be calculated by the same technique used for the maximum perpendicular magnetic flux density. The estimation result will be verified in the case studies.

III. Case Study

To check the validity of the proposed calculation, a case study of an HTS coil for a 15MJ SMES was carried out.

The HTS coil type designed for this case study was selected as toroid type coil having a high energy density in a small, the leakage magnetic field.

We assumed the 12mm-wide 2G HTS wire with 600 amps of critical current and the general magnetic field characteristic in this design.

We fixed the number of SPC and the inner diameter of toroid at 96 and 566 mm, respectively, at 96, as shown in Table I, so that we could change the inner diameter of SPC, operating current and number of turns of SPC in this SMES design.

To confirm the reduction of the time we presented required computation times by FEM and by the proposed method for the same model of the HTS coil for 15 MJ SMES system in this study.

TABLE I
Specification of 15MJ SMES

Number of SPC [ea]	Inner diameter of SPC [mm]	Inner diameter of Toroid [mm]	Operating Current [A]	Number of turns of SPC
	300		1690	173
	350		1680	156
	400		1690	141
	450		1680	130
96	500	566	1670	121
	550		1650	114
	600		1650	107
	650		1640	101
	700		1650	95

IV. Conclusion

In this article we suggest an easy and fast way to calculate a perpendicular magnetic field, stored energy and hoop stress in a toroid coil for a large scale SMES. We could achieve reduction in running time by using the proposed calculation method in comparison with the FEM. With this method, it is expected to significantly reduce the computation time required for the design, requiring iterative calculation of the optimal design of the HTS toroid type coil for a large scale SMES, within a reasonable estimation error.

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