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Analysis of an HTS coil for large scale superconducting magnetic energy storage

Ji-Young Lee[a], Seyeon Lee[a], Kyeongdal Choi[a], Sang Ho Park[a], Gye-Won Hong[a], Sung Soo Kim[a], Ji-Kwang Lee[b], and Woo-Seok Kim[*, a]

[a] *Korea Polytechnic University, 237 Sangidaehak-ro, Siheung, Gyeonggi-do, Korea*
[b] *Woosuk University, 443 Samnye-ro, Wanju-gun, Ceollabuk-do, Korea*

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Abstract

It has been well known that a toroid is the inevitable shape for a high temperature superconducting (HTS) coil as a component of a large scale superconducting magnetic energy storage system (SMES) because it is the best option to minimize a magnetic field intensity applied perpendicularly to the HTS wires. Even though a perfect toroid coil does not have a perpendicular magnetic field, for a practical toroid coil composed of many HTS pancake coils, some type of perpendicular magnetic field cannot be avoided, which is a major cause of degradation of the HTS wires. In order to suggest an optimum design solution for an HTS SMES system, we need an accurate, fast, and effective calculation for the magnetic field, mechanical stresses, and stored energy. As a calculation method for these criteria, a numerical calculation such as an finite element method (FEM) has usually been adopted. However, a 3-dimensional FEM can involve complicated calculation and can be relatively time consuming, which leads to very inefficient iterations for an optimal design process. In this paper, we suggested an intuitive and effective way to determine the maximum magnetic field intensity in the HTS coil by using an analytic and statistical calculation method. We were able to achieve a remarkable reduction of the calculation time by using this method. The calculation results using this method for sample model coils were compared with those obtained by conventional numerical method to verify the accuracy and availability of this proposed method. After the successful substitution of this calculation method for the proposed design program, a similar method of determining the maximum mechanical stress in the HTS coil will also be studied as a future work.

Keywords: SMES, Toroid, Magnetic Field, Stored energy

1. INTRODUCTION

A superconducting magnetic energy storage system (SMES) is well known as the highest efficient energy storage system with the fastest response time. The fast response of the SMES enables improved power quality of the electric power system by compensating the voltage dips or the frequency fluctuations. Many research and development projects have therefore been carried out to improve the power quality of micro grids. According to the previous studies, the capacity of the practical SMES should be over 5 MJ, at least to sufficiently compensate for the disturbances of the smallest micro power grid in Korea [1].

The single or multiple solenoids type coil is the simplest shape, among the various types of superconducting coils, to realize the high temperature superconducting (HTS) coil, which is the key element of the SMES. However, this type of coil has several issues that need to be overcome for application in a large scale HTS SMES of which the capacity is around 30 MJ or more [2]. One of the drawbacks of the solenoid superconducting coil is the high radial component of the magnetic flux density at the edge of the coil, which will have the major effect on the performance of the HTS conductor. The large stray magnetic field is another problem of the solenoid type HTS coil. Therefore, most of the development projects for the practical SMES coil take a toroid shape, which can minimize the highest radial component magnetic flux density on the HTS conductor in order to maximize the energy density of the HTS coil. The stray magnetic field from the toroid type coil can be decreased compared to that from the solenoid type coil [3].

However, the realization of the practical toroid type coil also includes other difficulties. First, it is difficult to wind the toroid shape HTS coil. Moreover, the estimation of the maximum radial component of the magnetic flux density applied on the HTS conductor is difficult. This estimation is essential for the design process of the HTS SMES coil because the maximum radial component of the magnetic flux directly affects the decision of the operational current density of the HTS SMES coil. The 3-dimensional topology of the toroid type coil causes difficulty, so we need a 3-dimensoinal numerical calculation to obtain the exact magnetic field distribution. The computer simulation calculation required such as finite element method (FEM) is very time consuming. Usually, the simulation of a toroid model coil can take minutes or hours at a time, depending on the size and complexity of the model. The optimization process of the design work generally needs hundreds of iterated calculations, so it may take several hours or even days to

* Corresponding author: wskim@kpu.ac.kr

obtain one set of optimal design parameters of an HTS SMES coil.

In this paper, we suggest a fast estimation method to obtain the maximum radial component of the magnetic flux density of the HTS toroid type coil. We assumed that the toroid type SMES coil will be assembled with a set of single pancake HTS coils arranged as a toroid form, which is the typical shape of the HTS toroid type coil. Because this type of arrangement has a periodic symmetry, each pancake coil has the identical maximum radial component of magnetic flux density at the same point in each local coordinate. The magnetic flux density at the arbitrary point could be calculated using the superposition of the magnetic flux densities generated at the point from each pancake coil. Using this method, we could reduce the calculation time considerably compared to the computation time with 3-dimensional simulation by FEM.

Similar to the preceding study “Calculation of Normal Fields to Superconducting Tape of Toroidal Type Winding With Circular Section" [4], but there is a difference between this paper, we used a statistical method to obtain a self field calculation mentioned in the M.N.Wilson’s book [5]. And the point of this paper is that we achieve a remarkable reduction of the calculation time by using this method.

2. CALCULATION OF MAGNETIC FIELD

2.1. Calculation of the maximum radial magnetic field

Because a typical HTS conductor as a wire for winding coil assumes the shape of a tape, the usual HTS coil forms single or double pancake winding. A number of HTS pancake coils are to be arranged as a toroid form and connected in series to realize a large scale HTS SMES coil. Fig. 1 shows a typical arrangement of the toroid type HTS coils with the design parameters such as diameter, number of pancake coils, and the radial build of each pancake coil. All of the design parameters in Fig. 1 used to define an HTS SMES coil are listed in Table 1.

The radial component of the magnetic flux density is very important because the critical current of the HTS tape is strongly affected by the magnetic flux density, which is applied perpendicularly on the surface of the HTS tape. According to the previous calculation result from the 3-dimensional FEM simulations, the general point at which the radial magnetic flux density of SPC becomes a maximum value is the mid-point of the side surface of each pancake coil. Fig. 2(a) shows the points of maximum radial magnetic flux density of SPC on a pancake coil.

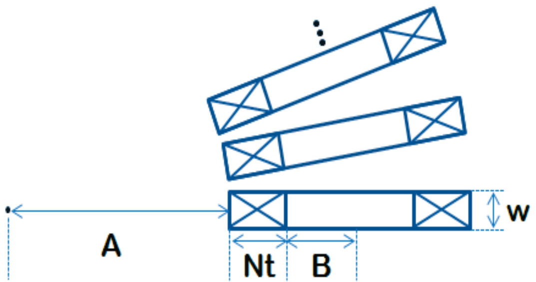


Fig. 1. Design parameters of the toroid type SMES HTS coil.

TABLE I
DESIGN PARAMETERS OF HTS TOROID SMES COIL.

Symbol	Quantity	Dimension
A	Inner radius of toroid	[mm]
B	Inner radius of pancake coil	[mm]
w	Width of HTS tape	[mm]
t	Thickness of HTS tape	[mm]
N	Number of turns of pancake	[turns]
I	Operating Current	[A]
SPC	Number of pancakes in toroid	[ea]

The maximum radial magnetic flux density of SPC at this point is actually the superposition of the magnetic flux densities from all of the pancake coils. According to the periodic symmetry, all the pancake coils are in the same condition, so we only need to calculate the maximum magnetic field in one pancake coil. We suggest calculating this maximum magnetic flux density using the summation of the self-field and the magnetic field generated from all the other pancake coils.**.**The self-field refers to the magnetic field from the pancake coil which contains the point to be calculated.

Because the self-field cannot be obtained using the analytic calculation, we considered numerical computation to obtain this value. However, numerical computation is time consuming, even for a simple pancake coil. We attempted to perform pre-calculations of a ratio of the central magnetic field and the maximum radial magnetic field as a function of the shape parameters of the single pancake coil using the numerical computation.

The central magnetic flux density in a pancake coil, B_0 in Fig. 2 (a), can easily be calculated by integrating the contributions from individual circular current filaments, to find

$$B_0 = J \cdot a \cdot F(\alpha, \beta) \qquad (1)$$

where

$$\mathrm{F}(\alpha, \beta) = \mu_0 \cdot \beta \cdot ln\left(\frac{\alpha + \sqrt{\alpha^2 + \beta^2}}{1 + \sqrt{1 + \beta^2}}\right) \quad , \qquad (2)$$

while $\alpha = b/a$, $\beta = w/2a$, and J is the average overall current density [5]. In order to find the radial maximum

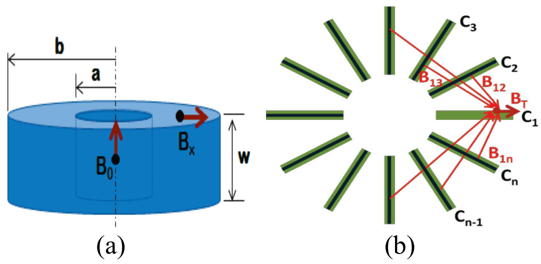


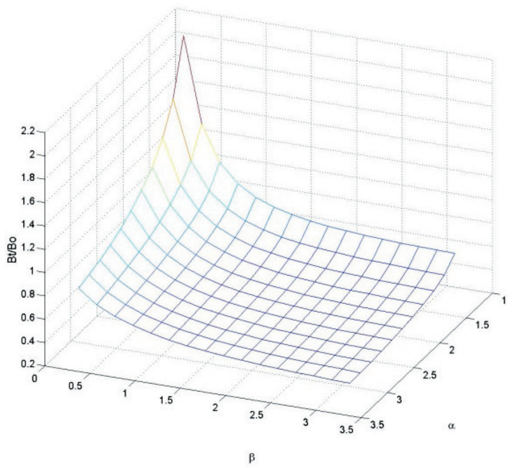
Fig. 2. HTS pancake coils for SMES; (a) single pancake coil, (b) arrangement of the HTS pancake coils for toroid type SMES coil.

flux density from the self-field, we need to find the ratio of the maximum radial magnetic flux density to the central magnetic flux density, B_x/B_0, as a function of α and β using the numeric computation.

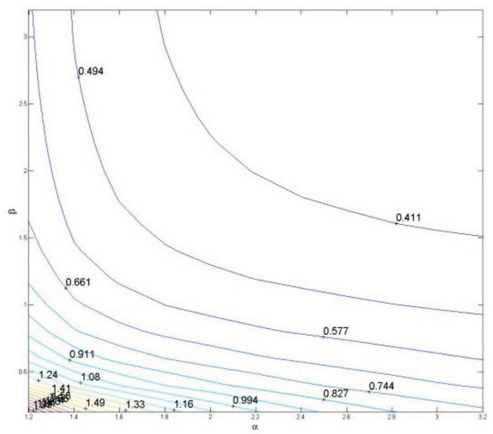
Fig. 3. shows graphs for the ratio, which is the function $T(\alpha,\beta)$ in this paper. We can derive the maximum radial magnetic flux density of SPC from the self-field by using this ratio, to find

$$B_{x,sf} = B_0 \cdot T(\alpha,\beta) \tag{3}$$

The maximum radial magnetic flux density of SPC from the other coils can be obtained by integrating the magnetic field with all the other current filaments. For simplification, we assumed that all the other pancake coils were circular line currents. Fig. 2(b) shows the contributions of all other pancake coils to the same point of maximum radial field. According to the line current assumption, we can integrate the individual contribution of each pancake coil.



(a)



(b)

Fig. 3. Plots of the ratio of the maximum radial magnetic flux density to the central magnetic flux density, B_x/B_0, as a function of α and β obtained by numeric computation; (a) 3-dimensional plot, (b) contour plot.

2.2. Calculation of External Field by other coils

We assumed a current in each pancake coil of the toroid type coil as a line current for calculation of the external field. We used the Biot-Sarvart Law, which is a basic law used to obtain the magnetic field produced by the coil current, which is expressed by (4). Therefore, we calculated the magnetic field directly at the mid-point of the C1 coil, as shown in Fig. 2(b), generated from the other pancake coil currents.

Fig. 4. shows the line currents in the toroid type coil in the Cartesian coordinate system.

The coil over the XZ plane is shown in Fig. 5(a) and is used to find the position coordinates of the line current coil placed in the toroid type in a Cartesian coordinate system. The gap of a differential current in the coil which is over the XZ plane is Φ and the coordination of the line current is (5).

$$(X, Z) = (R + r + r\cos\phi\,, r\sin\phi) \tag{4}$$

Similarly, Fig. 5(b) shows the coil which is over the XY plane.

The next coil which is relative to the coil in the X-axis is placed at a gap of θ. The position of the first coil in the XY plane is (5)

$$(X, Y) = (R + r + r\cos\phi, 0) \tag{5}$$

and the second position of the coil rotated by θ is (6).

$$(X, Y) = ((R + r + r\cos\phi)\cos\theta, (R + r + r\cos\phi)\sin\theta \tag{6}$$

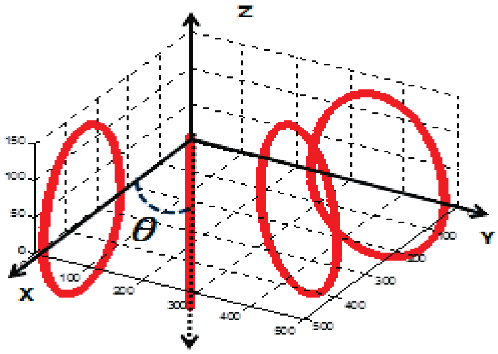
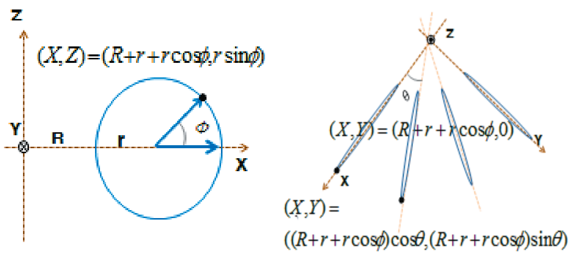


Fig. 4. Toroid type coil disposed in the XYZ space.



(a) (b)

Fig. 5. Toroid coil coordinates; (a) coil coordination in XZ plane plane ('R' is radius of toroid and 'r' is radius of SPC), (b) coil coordination in XY.

According to formulas (4) and (6), the position coordinates of the coil located in the toroidal type in a Cartesian coordinate system can be expressed as formula (7).

$$(X, Y, Z) = \big((R + r + r\cos\phi)\cos\theta, (R + r + r\cos\phi)\cos\theta, r\sin\phi\big) \qquad (7)$$

Using the coordinates of the coil obtained in formula (4), we calculate a magnetic field acting on the mid-point of C1 resulting from the C2,C3,…,Cn coil using the Bio-Sarvart Law.

$$dB = \frac{\mu_0}{4\pi}\frac{Id\vec{L} \times \hat{r}}{r^2} \qquad (8)$$

(μ_0: *permeability of air*, I: *current*, r: *location vectors*)

3. RESULT

The formula used to calculate the maximum perpendicular magnetic field is completed using the sum of the magnetic field in the self field and the other coil.

To compare with the perpendicular magnetic field according to the number of pancakes in the toroid calculated using the calculation method proposed in this paper and measured by FEM.

Fig. 6. shows that the perpendicular magnetic field calculated by a formula and FEM differ within an error of approximately 8%. As shown in Table.3, we represent the time required to run the MATLAB with the calculation method and using the FEM method. The FEM method takes more than 422 seconds, depending on the model, but running the MATLAB using the calculating method takes around 3 seconds. An improved speed of calculation time of 99 times can be expected.

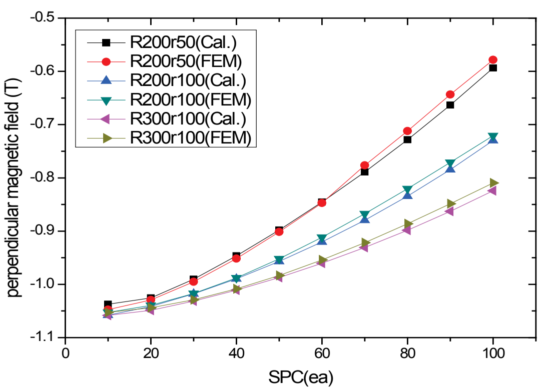


Fig. 6. Comparison of calculation results and FEM; perpendicular magnetic field according to number of SPC.

TABLE Ⅱ
MAXIMUM ERROR OF FEM AND CALCULATION.

Model	The maximum error(%)
R200, r50	3.4%
R200, r100	3.39%
R300, r100	8.08%

TABLE Ⅲ
COMPARISON OF TIME FROM FEM AND CALCULATION.

	FEM			Calculation		
Radius of Toroid, R[mm]	200	200	300	200	200	300
Radius of SPC, r[mm]	50	100	100	50	100	100
Number of SPC[ea]	80	90	100	80	90	100
Running Time[sec]	422	298	337	2.82	3.07	3.46

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We have assumed that SPC current is the line current but is actually the volume current. So that difference causes an error. In the next study we study for reducing the error, SPC current is composed of several lines current to simulate the volume current.

4. CONCLUSION

This paper suggests a fast estimation of a perpendicular magnetic field in a toroid coil for a large scale SMES. The calculation suggested in this paper showed a remarkable reduction (99% of calculation time with 3-D FEM) of running time by using an analytic and statistical calculation.

More detailed calibrations are still needed to improve the accuracy of the calculation. In addition, we carry out similar processes to obtain the stored energy and the maximum mechanical stress in progress.

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REFERENCES

[1] S. Kwak, S. Lee, W. S. Kim, J. K. Lee, C. Park, J. Bae, J. B. Song, H. Lee, K. Choi, K. Seong, H. Jung, and S. Y. Hahn, "Design of HTS Magnets for a 2.5 MJ SMES," *IEEE Transactions on Applied Superconductivity*, vol. 19, no. 3, pp. 1985-1988, 2009.

[2] S. Kim, "Analysis of Electromagnetic Characteristics of Large Scale Superconducting Magnetic Energy Storage," *M. S. Dissertation*, Korea Polytechnic University, Gyeonggi-do, Korea, 2013.

[3] K. P. Yi, J. S. Ro, S. Lee, J. K. Lee, K. C. Seong, K. Choi, H. K. Jung, and S. Y. Hahn, "A design methodology for toroid-type SMES using analytical andfinite element method," *IEEE Transactions on Applied Superconductivity*, vol. 23, no. 3, pp. 4900404, 2013.

[4] S. Lee, “Calculation of Normal Fields to Superconducting Tape of Toroidal Type Winding With Circular Section,” *IEEE Transactions on Applied Superconductivity*, vol. 20, no. 3, pp. 1888-1891, 2010.

[5] Martin N. Wilson, “Superconducting Magnets”, Clarendon Press, pp.20-21, 1983.