A Design Methodology for Toroid-Type SMES using Analytical and Finite Element Method

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***Abstract* — In this paper, a design methodology for toroid type SMES using analytical method and data table from finite element analysis is proposed. The method simplifies the model, and uses analytically derived equations to calculate the energy and center flux density. In order to determine number of turns and current using analytic process, perpendicular flux density and parallel flux density are obtain from data table.**

***Keywords* — toroid-type SMES, design methodology**

I. INTRODUCTION

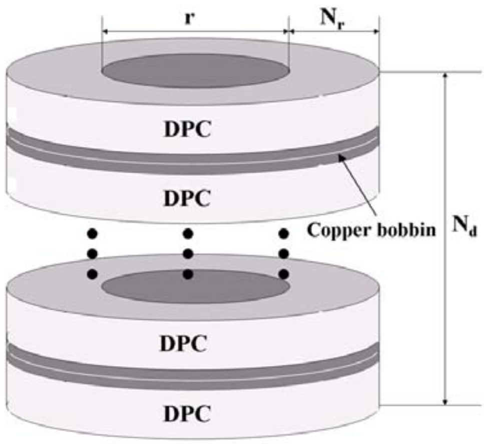
Superconducting magnetic energy storage (SMES) systems with high temperature superconductor (HTS) wires are one of the promising power system applications of superconducting technology and have been actively researched and developed worldwide.

Generally there are three types of SMES-solenoid, multiple solenoid, and toroid as shown in Fig. 1. Solenoid type is simple to design and easy to manufacture, but it cannot prohibit or confine stray field. Multiple solenoid-type shows very good characteristics on stray field in comparison with solenoid type, but it has very poor energy density. Modular toroid type, in which coils wind in pancake and stacked pancakes are configured, can be a compromise proposal. However it was known that toroid type requires more wire than solenoid type and multiple solenoid type. However toroid type can reduce normal field in the wire and stray field dramatically because magnetic field is confined within the coil. Therefore, the total length of wire in toroid type can be reduced in comparison with that in solenoid type by increasing operating current [1], [2].

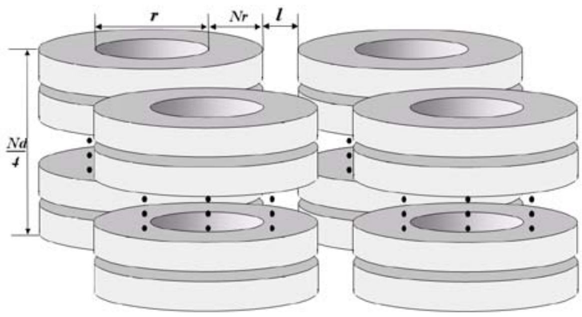
In this paper, a design methodology for toroid type SMES using analytical method and data table from finite element analysis is proposed.

II. A DESIGN METHODOLOGY FOR TOROID TYPE SMES

Designing toroid type SMES is considered more complicated than other types of SMES. It has more design variables than solenoid type SMES due to its pancake configuration as shown in Fig. 2. Also, unlike solenoid type SMES, it cannot be analyzed with 2D numerical method. Because of these two difficulties, an optimization of toroid type SMES takes tremendous amount of time.



(a) Solenoid type



(b) Multi solenoid type(four solenoids)

(c) Toroid type

Fig. 1. Various types of SMES.

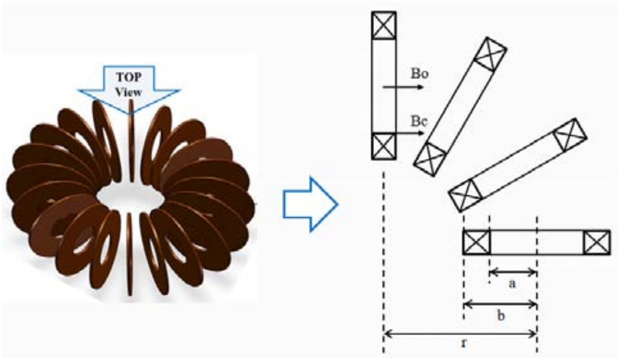


Fig. 2. Design variables of toroid type SMES.

A. Simplified model of toroid type SMES

In order to perform analytic analysis to toroid type SMES, it is necessary to simplify the model. The simplified model is shown in Fig. 3. The discrete pancakes are simplified into continuous toroid with ring shape emptiness within. If the number of pancakes increases and/or the thickness of the pancake increases, which leads to decrease of the space between the two adjacent pancakes, the difference of analysis result between the two models decreases. Also the analysis result of the original model can be estimate using superposition relationship between the two models.

B. Calculation of the energy and the center magnetic flux density

Normally, top priority of SMES design is the energy capacity of the SMES. Therefore, it is natural to take the first step of design from energy calculation. The following is energy density equation.

$$e = \frac{B_0^2}{2\mu_0} \qquad (1)$$

The energy density of the entire toroid is then:

$$E = \frac{B_0^2}{2\mu_0} \cdot \pi a^2 \cdot 2\pi r \qquad (2)$$

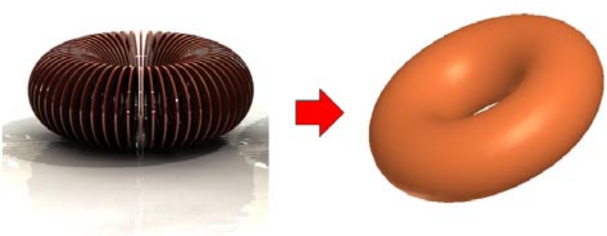


Fig. 3. Simplified model of toroid type SMES.

B_0 is the center magnetic flux density of the toroid type SMES as shown in Fig. 2, a and r is also shown in Fig. 2. Now we can calculate the required B_0 of the toroid SMES from (2).

C. Calculation of number of turns and current

With fixed a and r in Fig. 2, b is decided by thickness and number of turns N of the HTS wire. The relation between B_0 and N is:

$$\int B_0 r d\phi = B_0 2\pi r = \mu_0 NI \qquad (3)$$

$$B_0 = \mu_0 \frac{NI}{2\pi r} \qquad (4)$$

I is the current in each wire [3].

One of the major object of SMES optimization is amount of the HTS wires used in the system, which is connected directly to the cost of the SMES system. Therefore small N is favorable, which result in large I in order to maintain required B_0. From (4) it seems N can be decided very simply by using critical current of the HTS wire. However, it is not true because of the characteristics of HTS wire such as critical current vs. temperature and critical current vs. external flux density. The temperature rise is very critical, but it can be avoided by reducing losses and using right cooling system [4]. The external flux density, on the other hand, has to be considered carefully in this design step. Critical current of HTS wires decreases rapidly when the flux density on the wires increases. Critical current of HTS wire is affected not only by absolute value of the flux density, but also the direction of the flux. As shown in Fig. 4, HTS wire has different critical current value between perpendicular and parallel flux density with same magnitude.

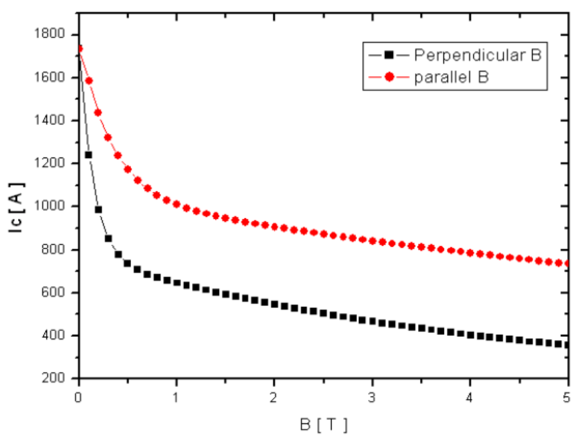


Fig. 4. Estimated B-Ic curve of 4-ply HTS wires at 20 K.

The flux density on the wire varies with I, therefore it is necessary to insert iteration procedure to decide right N and I. The procedure flowchart is shown in Fig. 5. The perpendicular flux density ($B_{\perp}$) and parallel flux density ($B_{\parallel}$) have to be calculated every steps, which means numbers of 3D numerical analysis is required for every model, resulting in rapid increase of the time required for optimization. This problem can be solved by making a data table of $B_{\perp}$ and $B_{\parallel}$ related to a, r, I and number of the pancakes. The data is obtained by finite element method (FEM) as shown in Fig. 6. The method is feasible because the $B_{\perp}$ and $B_{\parallel}$ show clear tendency with the variation of design variables, therefore precise value can be calculated by interpolating the roughly distributed data points. By using above methods, the toroid type SMES design can be performed using analytical process only. The data table is still under construction, and the result will be presented in the future.

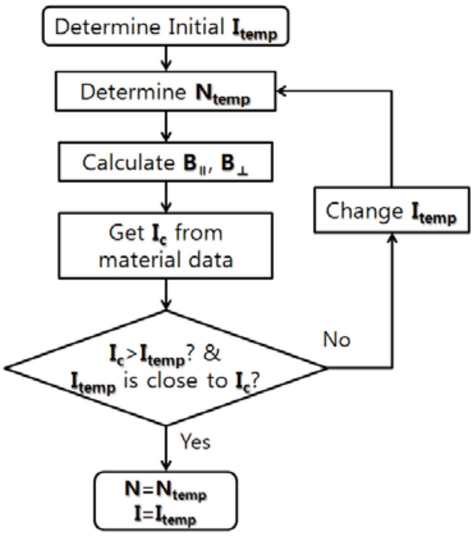


Fig. 5. Flowchart of deciding N and I.

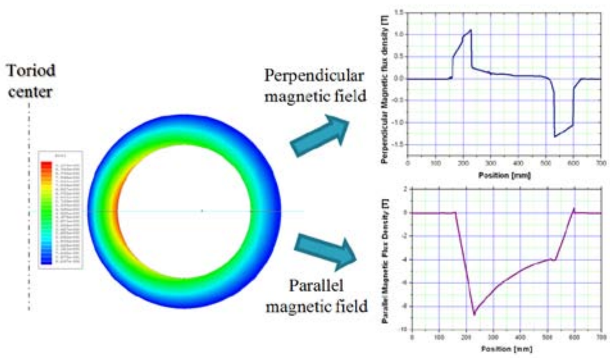


Fig. 6. Simplified model of toroid type SMES.

III. Conclusion

In this paper, a design methodology for toroid type SMES using analytical method and data table from finite element analysis is proposed. The method simplifies the model, and uses analytically derived equations to calculate the energy and center flux density. In order to determine number of turns and current using analytic process, perpendicular flux density and parallel flux density are obtain from data table.

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