Annals of the University of Craiova, Electrical Engineering series, No. 34, 2010; ISSN 1842-4805

CONCEPTUAL DESIGN OF 21 kJ SUPERCONDUCTING MAGNETIC ENERGY STORAGE DEVICE

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Abstract **– In this paper, a modular toroidal coil system is analysed for the development of a superconducting energy storage device (SMES) using FEM. The objective of this preliminary design is to determine the approximate dimensions, quantity of superconducting material, mechanical stresses and maximum magnetic fields around the superconductor, in order to optimize the configuration of SMES concerning the manufacturing cost. Three distinct variants were proposed for the shape coil: solenoid, multiple solenoids and toroid, pointing out there's advantages and disadvantages. Numerical analyse considers a modular toroid supporting the planar 2D modelling. The FEM implementation uses an equivalent rectangular cross section, conserving the inductance of the system. The modelling of perfect diamagnetism was made considering the values of relative permeability of superconductor close to zero. For automation of the numerical computation, a command file has been created using LUA scripting language. The numerical results indicate a maximum value of magnetic flux density localized in the frontal areas of the each solenoid coil and a low stray field level outside of modular toroidal coil. The 2D FEM modell used is useful for the identification of the critical values regarding the magnetic fields near the superconducting wire and the mechanical stresses.**

Keywords: *SMES, modular toroidal coil, FEM.*

1. INTRODUCTION

The main problem of the SMES device design is to determine the coil system geometry and the current distribution which produces a magnetic field below the critical limit of the superconducting material.
An optimized configuration of the superconducting magnet (SMES) must reduce as much as possible the volume of the superconducting material and the cost of this device [1].
On the other hand, the strong electromagnetic forces caused by high magnetic fields and coil current are a serious problem [2].
Regarding the superconducting materials, compared to the new generation of high critical temperature superconducting materials (HTS), at present only NbTi conductors (LTS) meet these requirements, but their operating temperature is low (4.2 K) using the liquid helium [3].

2. CHOISE OF COIL SHAPE

For shape of the coil, three distinct variants were proposed: solenoid, multiple solenoids and toroid.
Each option has advantages and disadvantages. For example, the perfect toroid has not stray field, but the manufacturing process is difficult and uses more wire than solenoid coil [4].

The intermediate option, modular toroid coil, uses multiple solenoidal coils arranged in toroidal geometry and connected in series.

The number and size of the multiple solenoid coils affect the size of SMES device, but the manufacturing process and feasibility of the design are favoured [5]. In this case, the stray field is still relatively small, but the modular toroid uses more wire than perfectly toroid coil [4].

For a 2D modelling and preliminary analysis, we consider a modular toroid consisting of 8 solenoids arranged symmetrically.
The equatorial cross section of this coil is presented in Figure 1, where D is the coil mean diameter and d winding diameter.
Each solenoidal coil is realized by NbTi superconductor (with Cu matrix). The specifications of such type of superconductor are presented in [6].
The optimization of the number and size of solenoids will be studied after experimental validation of this model.
In the first phase, the ratio d/D = 0.5 is adopted.
This ratio is favourable for volume and centering force [7].

3. NUMERICAL MODELLING

The numerical analyse was performed using FEM implemented in FEMM software.
The modular toroid does not supports axisymmetric modelling.
The working 2D model describes a rectangular cross section toroid which supports planar modelling.
For this type of toroids, the characteristic dimensions are shown in Figure 2a, where D is the coil mean diameter, l is the coil winding width and h is the coil winding height.

For this model, the value h of the winding height, same with the software “depth” parameter, is determined under assumption of equality between the inductance of the complete circular cross section toroid and rectangular cross section toroid.

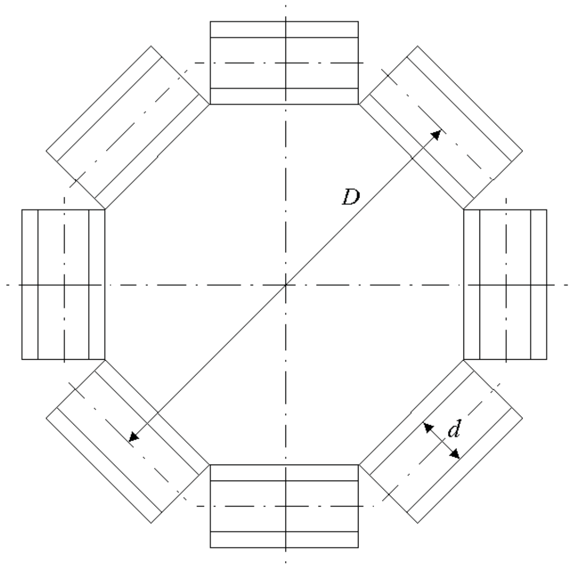

Figure 1: Equatorial cross section of modular toroid.

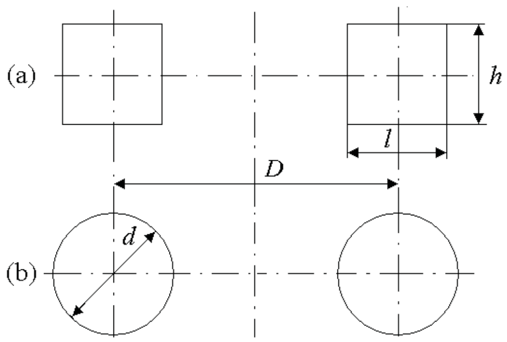

Figure 2: Rectangular cross section toroid (a), circular cross section toroid (b).

The inductance L_c of the circular cross section toroid, with thin winding (Figure 2b), can be calculated by [8]:

$$L_c = \frac{\mu_0}{2}\left[D^2 - \sqrt{D^2 - d^2}\right] \tag{1}$$

To facilitate the calculation, we propose a rectangular cross section toroid modell with the winding width $l = d$. The inductance L_r of this model is calculed by [9]:

$$L_c = \frac{\mu_0}{2\pi} h \ln\frac{D+d}{D-d} \tag{2}$$

From equality:

$$L_c = L_r \tag{3}$$

we get:

$$h = 0.766\, d \tag{4}$$

The modelling of perfect diamagnetism was made considering the values of relative permeability of superconductor close to zero. We adopted the value $\mu_r = 10^{-7}$. This value is sufficient for expulsion of magnetic field from superconducting domain.

The operating current density in superconductor was considered J = 500 MA/m^2. According to specifications presented in [6], the critical current density of NbTi superconductor at T = 4.2 K and B = 7 T is J_c = 530 MA/m^2 .

To reduce the gauge of the toroidal SMES, we adopte a coil mean diameter D = 0.3 m and implicitly the winding diameter d = 0.15 m.

The value of the “depth” parameter is given by the relation (4).
For automation of the numerical computation, a command file has been created using LUA scripting language. This allows multiple runs to be executed easy and changing any of the parameters is carried out only by changing a line in the command file. The mesh was realised using 19847 triangular elements.

4. RESULTS OF SIMULATION

The distribution of magnetic flux density is presented in Figure 3.

A first analysis indicates that the maximum value of magnetic flux density is about 4.68 T, localized in the frontal areas of the each solenoid coil. In this case of the stationary regime, the magnetic flux density does not exceed the critical conditions of superconducting phase.
It should be noted that is necessary to ensure that the critical values does not exceed during transient regimes, as a condition for maintaining the superconducting state [10].
On the other hand, the device can be appreciated for the low stray field level outside of modular toroidal coil.

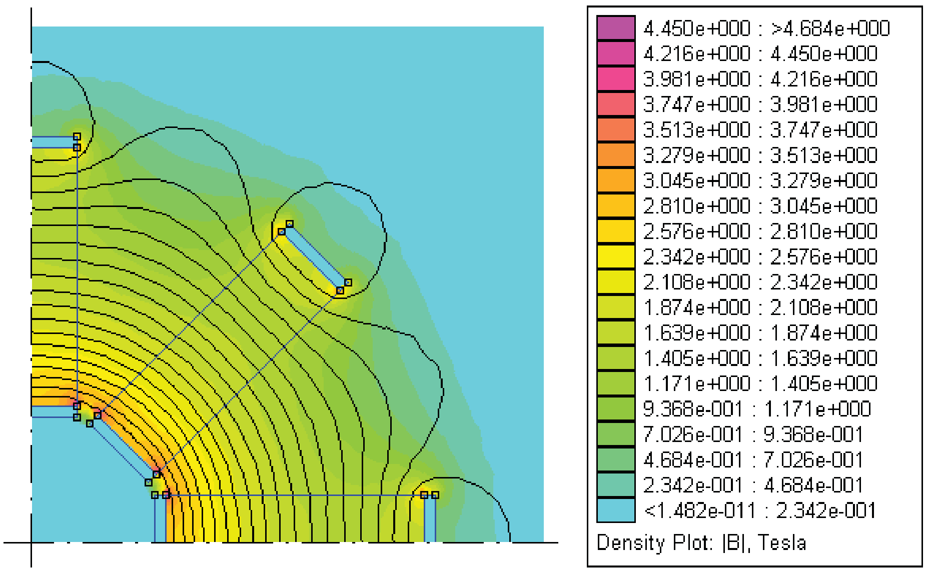

Figure 3: Distribution of magnetic flux density.

4. CONCLUSIONS

The modelling and simulation by 2D FEMM software is simple and easy using an automation of the numerical computation by association with Lua scripting language. In this way, may be modified the geometry, dimensions and the number of solenoid coils.
Whatever degree of accuracy, it provides preliminary information about areas of intense magnetic fields that threaten the superconducting phase.
More, after experimental validation, the working 2D modell used in FEMM software is useful for the identification of the critical values regarding the magnetic fields near the superconducting wire and the mechanical stresses.

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