Three Dimensional Numerical Solution for Maximum Magnetic Field of 21 kJ Superconducting Magnetic Energy Storage Device

Alin-Iulian Dolan[*] and Florian Stefanescu[†]
[*] University of Craiova/Electrical Engineering Faculty, Craiova, Romania, adolan@elth.ucv.ro
[†] University of Craiova/Electrical Engineering Faculty, Craiova, Romania, florian@elth.ucv.ro

***Abstract* - To develop an optimized configuration of superconducting magnetic energy storage (SMES) device concerning the volume of the superconducting material and its cost, a two-dimensional numerical model was created in [11] using the finite element method in FEMM software. For numerical implementation, some geometrical parameters of the modular toroidal coil system were established under assumptions of equality between the inductance of the complete circular cross section toroid and rectangular cross section toroid. In this paper, a three-dimensional numerical solution for maximum magnetic field of the real geometry of the modular toroidal coil system is obtained using finite element method in ANSYS software. The MVP-edge based formulation has been employed for computing the static magnetic field. For minimize the work time, different amounts of additional memory have been used during the analyze, via an ANSYS configuration file. The results validate well enough the previous two dimensional numerical solution obtained with FEMM software and, consequently, its assumptions. Comparison of the two numerical models is made, highlighting the effectiveness of two-dimensional model concerning the work time and the hardware resources requirement. The advantage of three-dimensional modeling is the possibility of description of real geometry, but this can be counterbalanced by well-chosen assumptions for a two-dimensional model.**

Keywords - *SMES, modular toroidal coil, 2-D and 3-D FEM modeling*

I. 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].

To this purpose, a two-dimensional numerical model was created in [11] using the finite element method in FEMM software.

In this paper, a three-dimensional numerical solution for maximum magnetic field of the modular toroidal coil system is obtained using ANSYS software.

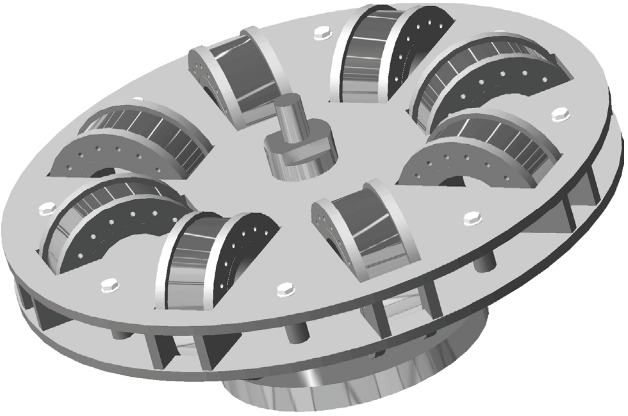

Fig. 1. Modular toroid coil three-dimensional view.

The results are compared with two-dimensional numerical solution given by FEMM software and some considerations are made regarding the effectiveness of two-dimensional model and its assumptions.

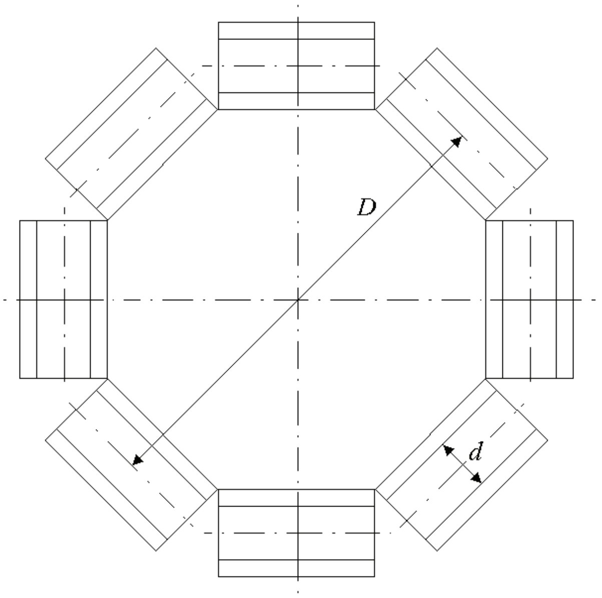

Fig. 2. Modular toroid coil cross section [11].

Also, a comparison between two-dimensional and three-dimensional computations concerning the work time and hardware resources requirement are presented.

For shape of the coil, a perfect toroid was chosen. As intermediate options, the modular toroid coil uses multiple solenoidal coils arranged in toroidal geometry and connected in series. Each solenoidal coil is realized by NbTi superconductor (with Cu matrix).

For the FEM modeling and preliminary analysis, it was considered a modular toroid consisting of eight solenoids symmetrically arranged (Fig. 1). The optimization of the number and size of solenoids will be studied after experimental validation of this model.

The equatorial cross section of this coil is presented in Fig. 2, where D is the coil mean diameter and d is the winding diameter.

II. NUMERICAL MODELING

A. *Two-dimensional numerical model*

An earlier two-dimensional planar model used in FEMM software describes a rectangular cross section toroid [11]. For this type of toroids, the characteristic dimensions are shown in Fig. 3a, where D is the coil mean diameter, l is the coil winding width and h is the coil winding height.

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 (Fig. 3b) and rectangular cross section toroid (Fig. 3a).

To facilitate the calculation, it was proposed a rectangular cross section toroid model with the winding width:

$$l = d \tag{1}$$

From equality of the two inductances it was obtained:

$$h = 0.766d \tag{2}$$

The modeling of perfect diamagnetism was made considering the value of relative permeability of the superconductor close to zero. It was adopted the value $\mu_r = 10^{-7}$. This value is sufficient for expulsion of magnetic field from superconducting domain (Fig. 6).

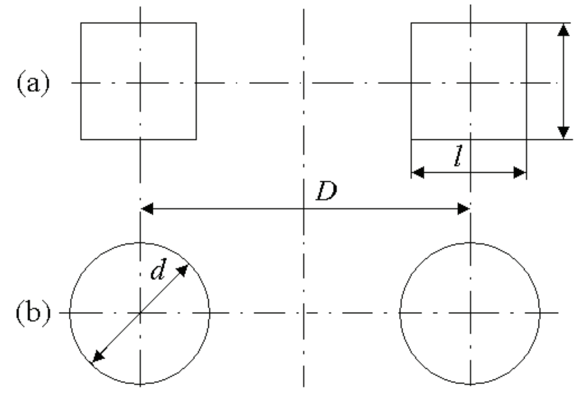

Fig. 3. Rectangular cross section toroid (a), circular cross section toroid (b) [11].

The operating current density in superconductor was taken J = 381.548 MA/m^2. According to specifications presented in [6], the critical current density of NbTi superconductor at T = 4.2K and B = 7T is J_c = 530MA/m^2.

To reduce the gauge of the toroidal SMES, it was adopted a coil mean diameter D = 0.142 m and implicitly the winding diameter d = 0.04 m. The value of the "depth" parameter is given by the relation (2).

To facilitate the numerical computation, a command file has been created using LUA scripting language. The mesh was realized using 17856 nodes and 35066 triangular elements.

B. *Three-dimensional numerical model*

The three-dimensional model of real geometry (Fig. 4) is realized using ANSYS software and for the analysis of static magnetic field of the coil, the MVP-edge based formulation has been employed.

The MVP-edge based formulation associates degrees of freedom with element edges rather than element nodes. It is often considered as better than the MVP nodal-based formulation in the cases of presence of media of different properties due to its main advantage: the elimination of the difficulty of a gauged magnetic vector potential with nodal elements in satisfying the interface conditions on iron/air interfaces, by allowing the normal component of the vector potential to be discontinuous on these interfaces [12].

Additionally, the edge element formulation is superior to the nodal element one from the standpoints of the computer storage and the CPU time [12].

In this case, the numerical computation has been obtained by creating command files using APDL (ANSYS Parameter Design Language).

The mesh was realized using tetrahedral elements (Fig. 5). The thirty-two-th part of model was analyzed, a thirty-two time reduction of the nodes number being obtained. The number of nodes and of tetrahedral elements is 533446, respectively 392147, being limited by hardware resources.

In the analyzed domain, the flux normal conditions have been considered for the sides forming a sharp angle and the flux parallel conditions, for the others (Fig. 4).

The computations were run on a PC with 1.5 GB RAM and 1.83 GHz frequency processor. The memory management has direct implications on the work time. When the model requires, additional memory is used from system virtual memory (PC hard disk) to supplement physical memory. This affects strongly the speed performances of the solver, so, only a minimum necessary amount of additionally memory must be allocated [12].

For minimize the work time, different amounts of additional memory have been used during the three numerical analyze phases: pre-processing, processing and post-processing, via an ANSYS configuration file.

III. RESULTS OF SIMULATION

Simulating again the perfect diamagnetism by condition $\mu_r = 10^{-7}$, the distribution of three-dimensional static magnetic flux density is presented in Fig. 7. The computed maximum value of magnetic flux density is 7 T, being located on the interior round corner of the solenoid coil, closest to the toroid center (Fig. 7 – detail).

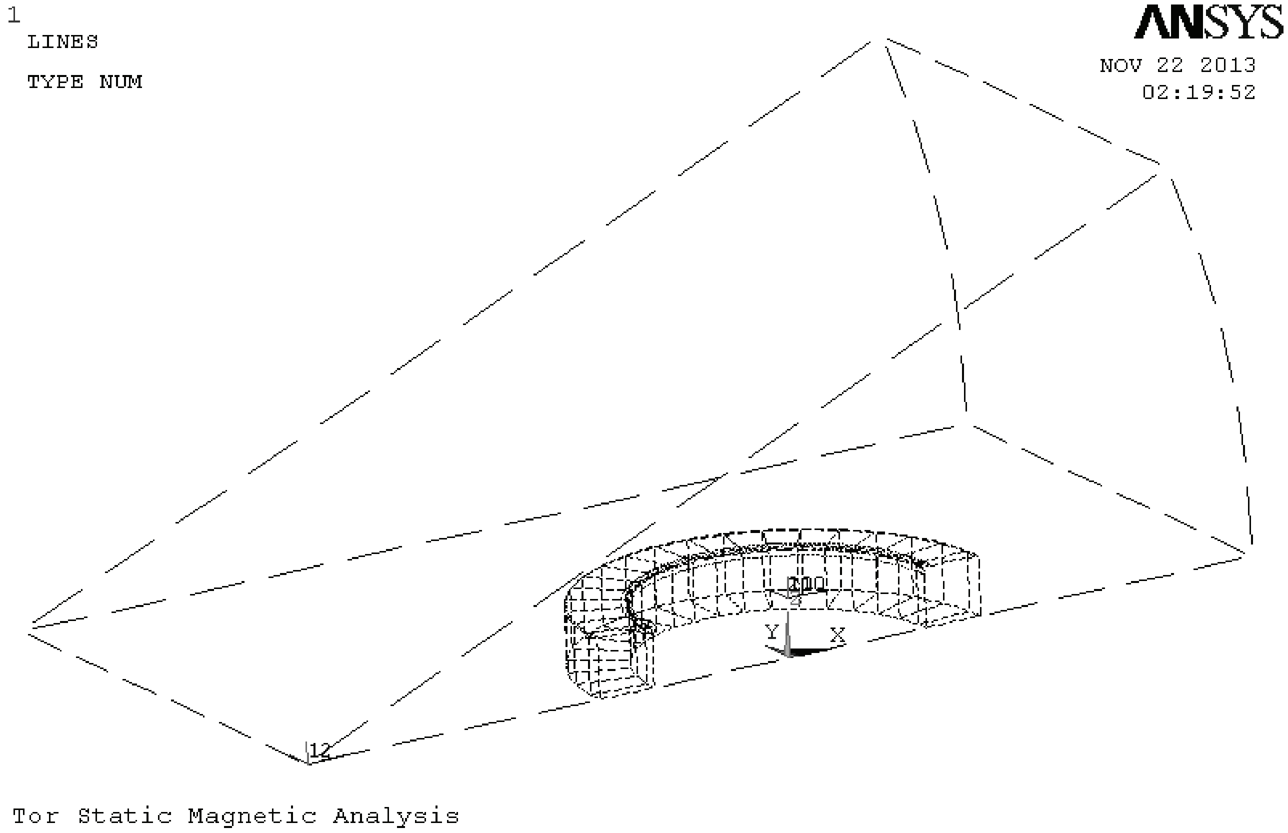

Fig. 4. Three-dimensional ANSYS geometry.

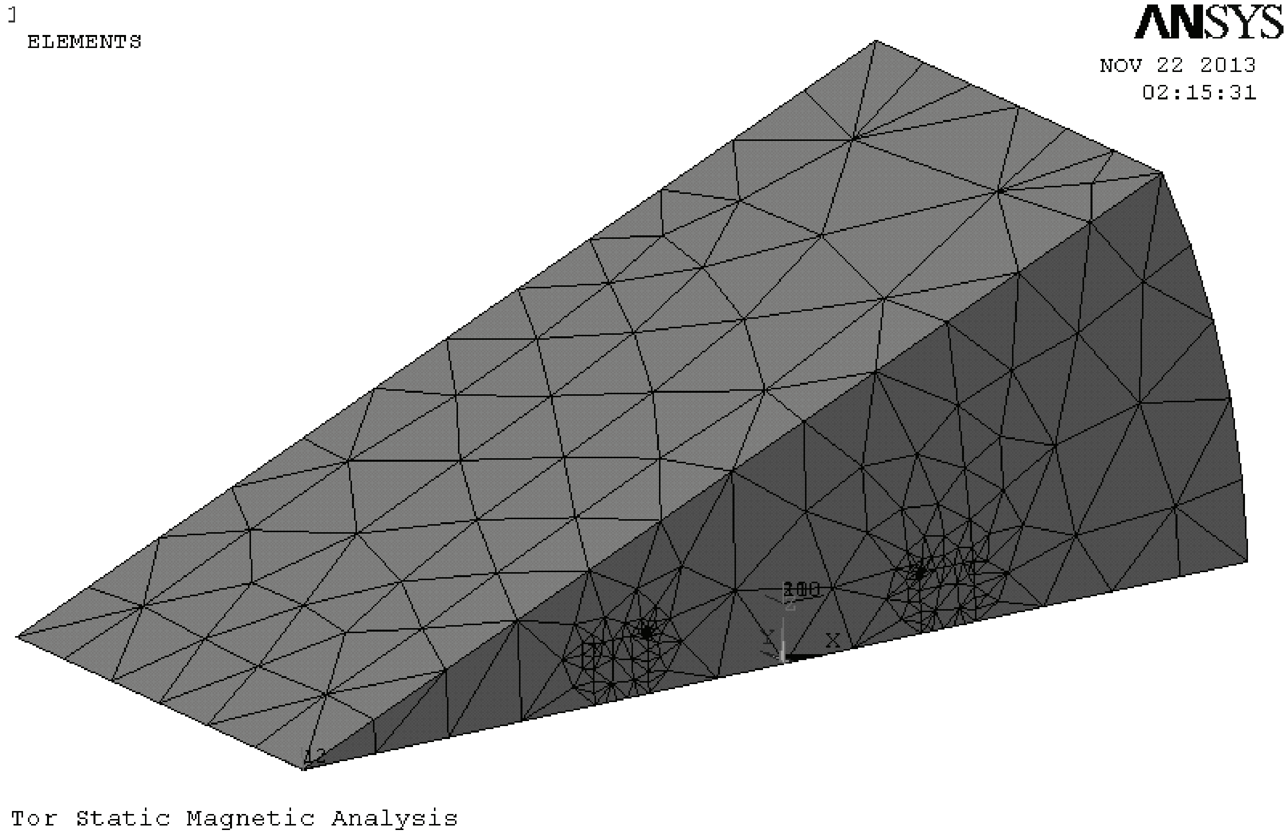

Fig. 5. Three-dimensional ANSYS mesh.

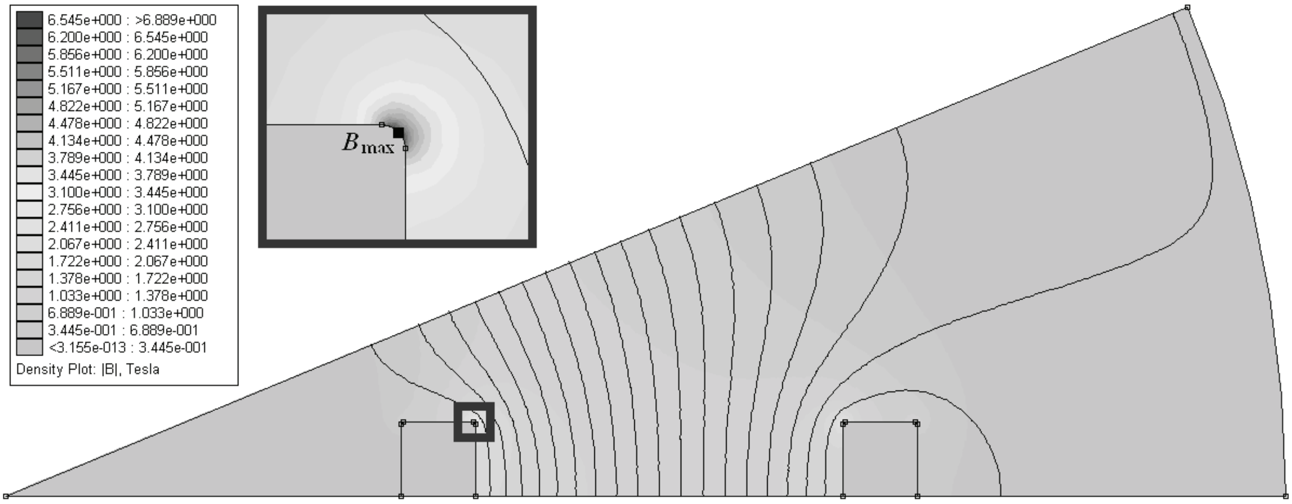

Fig. 6. Distribution of magnetic flux density and detail (two-dimensional FEMM).

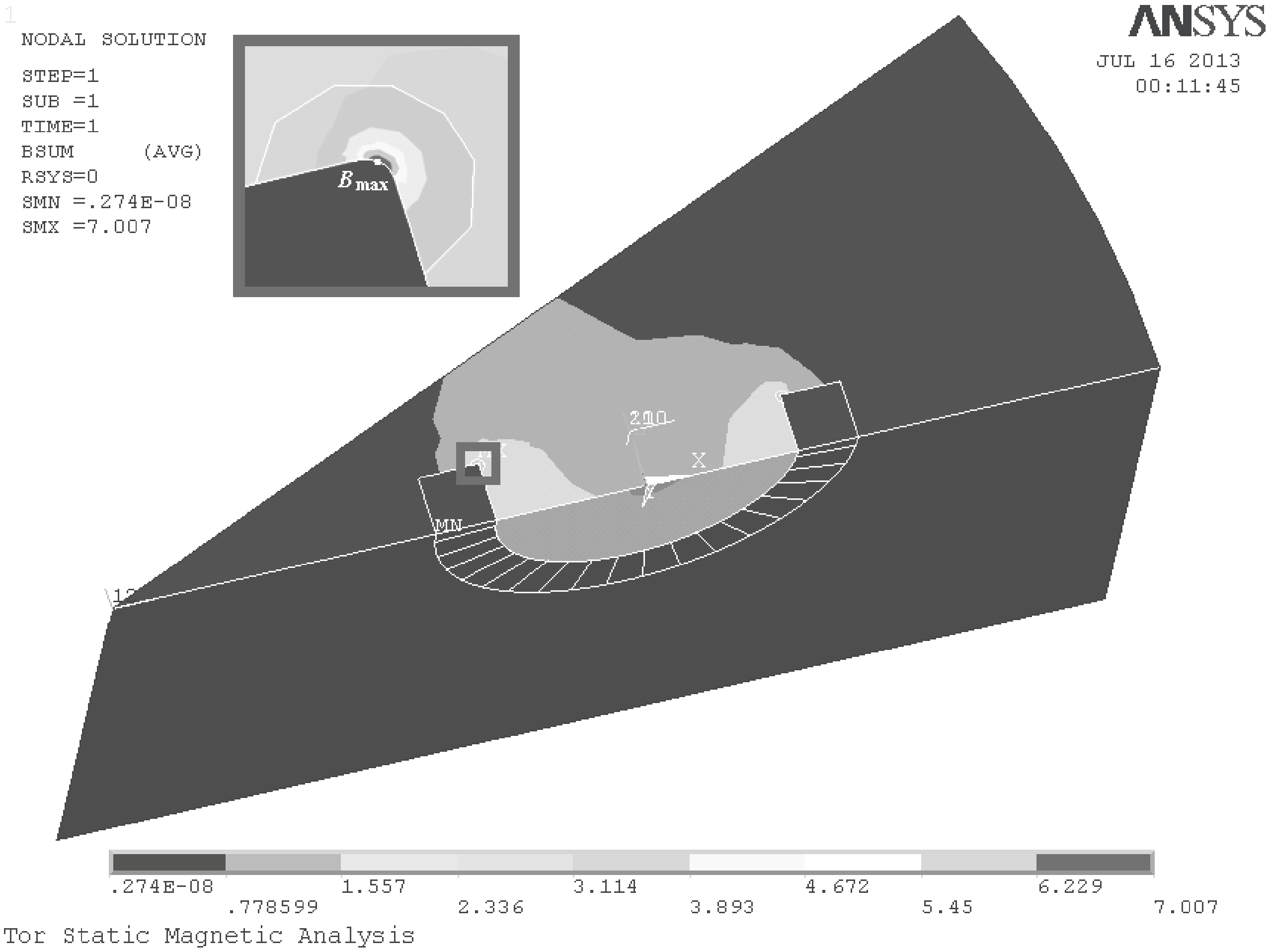

Fig. 7. Distribution of magnetic flux density and detail (three-dimensional ANSYS).

This value can be compared with the previous two-dimensional finite element method result, obtained using FEMM software that was 6.9 T in the same conditions, being located in the same region (Fig. 6 – detail).

That validates also the assumptions concerning equality between the inductance of the complete circular cross section toroid and rectangular cross section toroid, taken into account in the two-dimensional planar modeling.

On the other hand, the two-dimensional model is much easier and faster than the three-dimensional model, which requires important level of RAM. For example, if two-dimensional simulation takes some seconds, the three-dimensional result with optimized work time is obtained after more than one hour.

The advantage of three-dimensional modeling is the possibility of description of real geometry, but this can be counterbalanced by well-chosen assumptions for a two-dimensional model.

It should be noted that in this case of the stationary regime, the magnetic flux density does not exceed the critical condition of superconducting phase. Also, it can be appreciated the low stray field level outside of modular toroidal coil.

IV. CONCLUSIONS

A three-dimensional numerical solution for maximum magnetic field of a modular toroidal coil system is obtained using three-dimensional finite element method (ANSYS software) for the development of a superconducting energy storage (SMES) device.

The results validate a previous two-dimensional numerical solution (FEMM software) obtained under assumptions of equality between the inductance of the complete circular cross section toroid and rectangular cross section toroid (error of 1.48%).

This shows that a two-dimensional model with well-chosen assumptions can be as accurate as a three-dimensional model of a real geometry, expensive in terms of work time and hardware resources.

The modeling by three-dimensional ANSYS software or by two-dimensional FEMM software is facilitated using the automation of the numerical computation by association with APDL, respectively, LUA. In this way, it may be much easier to modify 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 three-dimensional and two-dimensional models used in ANSYS and FEMM software products are useful for the identification of the critical values regarding the magnetic fields near the superconducting wire and the mechanical stresses.

REFERENCES

[1] C. A. Borghi, M. Fabbri and P. L. Ribani, “Design optimisation of a microsuperconducting magnetic energy storage system”, *IEEE Transaction on Magnetics,* vol. 35, no.5, pp. 4275-4284, 1999.

[2] M. Fabbri, D. Ajiki, F. Negrini, R. Shimada, H. Tsutsui and F. Venturi, “Tilted toroidal coils for superconducting magnetic energy storage systems”, *IEEE Transaction on Magnetics,*, vol. 39, no.6, pp. 3546-3550, 2003.

[3] P. Tixador, “Superconducting magnetic energy storage: Status and perspective”, *IEEE/CSC & ESAS European Superconductivity News Forum*, no. 3, January 2008.

[4] J. H. Kim, S. Y. Hahn, C. H. Im, J. K. Kim, H. K. Jung and S. Y. Hahn, “Design of 200 kJ HTS SMES system”, *IEEE Transactions on Applied Superconductivity*, vol. 12, no. 1, pp. 774–777, 2002.

[5] R. L. Causley, C. Cook and S. A. Gower, “Design of a high temperature superconductor magnetic energy storage system”, *Proceedings of the Australasian Universities Power Engineering Conference (AUPEC-2001) – Perth*, September 23 – 26, pp. 322-325, 2001.

[6] S. Nomura, H. Tsutsui, S. Tsuji-Iio, H. Chikaraishi and R. Shimada, “Feasibility study on high field magnets using stress-minimized helical coils”, *Proceedings of the Fifteenth International toki Conference on "Fusion and Advanced Technology",* vol. 81, no. 20-22, pp. 2535-2539, 2006.

[7] M. Shimizu, Y. Tanabe, T. Yoshioka, K. Takeda, T. Hamajima, N. Miki, Y. Nakayama, M. Udo, N. Takeda, H. Miyazaki, K. Kamemura and M. Yamamoto, “Feasibility study of a 10-GWh toroidal superconductive magnetic energy storage system 1. System design”, *Physics Journal, 8th International Conference on Magnet Technology,* vol. 45 (C1), pp. 581-585, 1984.

[8] Floch, A. Lacaze, Y. Laumond, J. M. Kauffmann and P. Hiebel, “Dimensionnement et réalisation d'un SMES impulsionnel de 500J”, Eur. Physical Journal Applied Physics, vol. 2, no. 1, pp. 17-25, 1998.

[9] F. E. Terman, *Radio Engineer's Handbook,* McGraw-Hill, New York, 1943.

[10] F. Stefanescu, “Systemes de Stokage de l’energy electrique”, *9th International Conference on Applied and Theoretical Electricity and 11th Symposium on Cryoelectrotechnics and Cryogenics, Craiova, October, 08-10, 2008*, *Annals of the University of Craiova, Series: Electrical Engineering,* no.32, pp. 337-341, 2008.

[11] F. Stefanescu and A. I. Dolan, “Conceptual design of 21 kJ superconducting magnetic energy storage device”, *Annals of the University of Craiova, Series: Electrical Engineering,* no. 34, pp. 109-112, 2010.

[12] ANSYS Documentation, *ANSYS, Inc. Theory Reference.*