New shape of superconducting coil with improved critical current – design and FEM analysis results

B Grzesik and M Stepień
The Silesian University of Technology,
Department of Power Electronics, Electrical Drives and Robotics,
44-100 Gliwice, B. Krzywoustego 2
E-mail: boguslaw.grzesik@polsl.pl; mariusz.stepien@polsl.pl

Abstract. The novel superconducting HTS coil designed for Superconducting Magnetic Energy Storage (SMES) is the aim of the paper. Novelty lies in the shape of the coil that minimises perpendicular component of the flux density of HTS wire. In this paper authors try to find the shape of the coil where perpendicular component of magnetic field is as close as possible to zero. Proposed solution has the helical shape of coil turns and the special shape of the magnetic core (magnetic core with air gap is needed for increasing stored energy). Helical turns are put on toroidal former and then magnetic core on it. Each turn has the same shape, length and is put in the same magnetic flux. Near-uniform distribution of magnetic flux is the result of the shape of winding and also non-uniform shape (or non-concentric) of magnetic core that has multiple radial air gaps. It produces magnetic field distribution in magnetic core shaped coaxially to winding and distribution of stored magnetic energy uniformly on magnetic core circumference. Magnetic energy is stored in air gaps and proposed shape of core is the best solution of core but its fabrication produces technological difficulties in core manufacturing.

1. Introduction
The most popular industrial application of HTS wire is based on BiSCCO tapes. This type of superconducting wire shows many advantages and one meaningful drawback. It is sensitivity of critical current in wire on direction of magnetic field. Many efforts are focused on shaping of magnetic field properly to HTS windings [1], [2]. This work shows different approach. It consist in shaping of HTS windings due to magnetic field direction. This solution in comparison with earlier known ones needs more complicated manufacturing process but shows higher utilization of HTS wire.

Presented here HTS coil, assigned to energy storage system, is considered as coil with magnetic core. The material of magnetic core, amorphous, operates in liquid nitrogen (LN2). It is important advantage of coil in respect of cooling system.

Presented here results were obtained using FEM method. The axial symmetry 2D model was used.

2. Motivation
The stacked double pancake technique is mostly used in design of HTS coils. Its advantage is very simple fabrication process but magnetic field near extreme pancakes (top and bottom) decreases considerably critical current of whole coil (pancakes are connected in series). The shape of coil with homogenous magnetic field in whole coil could gives maximum possible value of critical current.
Novel shape of coil presented in this paper has a homogenous magnetic field in the winding, therefore authors decided to undertaken research work devoted proposed coil.

3. The state-of-the-art
Many works on HTS coils are focuses on double pancake solution, i.e. [1]. Because magnetic field is non-homogenous at the end of such arranged coil many efforts are directed to coil design where magnetic flux at the end of coil is parallel to the wire in pancake windings. The solution where magnetic field is shaped by proper arrangement of coil and its positioning in magnetic core is work [2]. Another solution is the coil called as U-shape coil [3]. It improves magnetic field but magnetic field is parallel to wire only in the middle of coil. Design of coil with fully homogenous field, parallel to windings was proposed by authors of this paper [4].

4. HTS coil idea and design
The idea of coil where magnetic field is homogenous in whole coil and parallel to HTS wire is coil having toroidal shape. The coil is depicted in figure 1 (each turn of coil winding is in different color). Windings of coil are located on torus surface and each of turn is helical in shape.

Figure 1. Idea of new shape of superconducting coil

The coil presented in figure 1 is single layer one. It has very small inductance. To obtain higher value of inductance two solution are possible. The first one is multilayer coil, the second one is the coil with magnetic core. Very high value of inductance is obtained for multilayer coil with magnetic core. Half cross-section of multilayer coil windings is shown in figure 2 and coil with magnetic core is shown in figure 3.

Figure 2. Cross section of multilayer coil
The homogeneity of magnetic field can be obtained in proposed coil for high value of ratio of major radius $R$ to minor radius $r$ of coil torus ($R/r > 50$). Magnetic flux lines in coil inserted into coaxial core is depicted in figure 4. Non concentric flux lines increase strongly perpendicular component of flux density and critical current has to be reduced. Flux lines could be shaped concentrically by adding magnetic core and proper design of its shape. Detailed description of magnetic core design assigned to the coil is presented in next section.

**Figure 3.** Helical coil with magnetic core

5. Design of magnetic core for HTS coil

New magnetic materials, for instance amorphous metals, allow operation of magnetic core in low temperature. It simplifies design of coil with magnetic core because of no thermal insulation in between core and winding. It is assumed that the coil operates at 77 K.

In case both the coil and the magnetic core are of toroidal shape the resultant magnetic flux is not coaxial in relation to coil wires. The only solution is to use non-concentric magnetic core with certain number of small air gaps. The magnetic core is depicted in cross-section in figure 5. Number and size of air gaps are calculated by FEM to obtain the best distribution of flux lines. Magnetic flux lines and magnetic flux density distribution in coil with modified magnetic core are shown in figure 6 and figure 7 respectively.

**Figure 4.** Flux lines in HTS winding of coil with concentric magnetic core
The serious drawback of this design is difficult process of fabrication. Mechanical properties of new magnetic materials and possibilities of modern technology allow the machining of small size air gaps in magnetic material. The magnetic gaps are filled with electric insulation. Beside of shaping of magnetic field air gaps in magnetic core are store magnetic energy of coil. Detailed description of this phenomenon is presented in the next section.

Flux density distribution in figure 7 reveals “hot-spots” of flux density in HTS windings region. Because of serial connection of turns critical current of whole coil is permitted by turn placed in the highest magnetic field. To increasing critical current longer distance between windings and core is needed.
6. Magnetic energy storage in the coil

The described coil is dedicated to magnetic energy storage (SMES). For coreless coils energy is stored with small density in large space around coil. Magnetic core with air gaps close near whole energy in gaps between magnetic material. Distribution of stored magnetic energy in the core described in details in previous section is shown in figure 8. Multiple air gaps results in uniform distribution of energy along coil circumference. The energy distribution is given for coil of 355 mH of inductance and 100 A of coil current. Total stored energy was 1.7 kJ. Near 99% of energy was stored in air gaps of magnetic core.

![Figure 8. Magnetic energy stored in air gaps along circumference of HTS coil](image)

7. Conclusions

The following conclusion were stem from presented work

- New shape of HTS coil for magnetic energy storage system was developed
- Helical shape of coil is way to obtain higher current density in coil wire.
- Special shape and arrangement of magnetic core has been proposed
- Magnetic energy of coil is stored in air gaps arranged along circumference of coil
- Important drawback of coil is the difficulty of manufacturing multilayer coil and magnetic core with small size air gaps.

References

[1] Oswald B et al 2006 AC Application of HTS Conductors in Highly Dynamic Electric Motors *Journal of Physics: Conference Series* 43 (2006) pp 800–803

[2] Friedman A Shaked N Perel E Gartzman F Sinvani M Wolfus Y Kottick D Furman J and Yeshurun Y 2003 HT-SMES operating at liquid nitrogen temperatures for electric power quality improvement demonstrating, *IEEE Transactions on Applied Superconductivity* vol 13 issue 2 pp 1875 – 1878

[3] Wen T C 2005 Development of an Electromagnetic Energy Storage System, *Project Report, Department of Electrical and Computer Engineering University of Auckland, New Zealand*

[4] Biskup T Buhler C Grzesik B Krijgsman J Michalak J Pasko S Stepień M and Zygmanowski M 2004 Analysis of Inductance and Magnetic Field Distribution in the Superconducting Coil Assigned for Energy Storage Applications *EPE-PEMC’04, Conference Riga, Latvia*