Journal of Materials Processing Technology 161 (2005) 28–32

Journal of Materials Processing Technology

www.elsevier.com/locate/jmatprotec

Design of a laminated-steel magnetic core for use in a HT-SMES

A. Friedman*, M. Zarudi, N. Shaked, M. Sinvani, Y. Wolfus, Y. Yeshurun

Institute of Superconductivity, Bar-Ilan University, Ramat-Gan 52900, Israel

Abstract

Since mid-1990s there was an impressive progress in manufacturing high-temperature superconducting (HTS) wires. However neither their prices nor properties still do not allow manufacturing efficient superconducting magnetic energy storage devices (SMES's). One of the ways to increase the stored energy of the coil and reduce the cost of SMES lies in the use of a magnetic core. We found that the so-called pot-core configuration simultaneously minimizes a volume of the core and magnetic field on the winding. Two laboratory models of an SMES's with a ferromagnetic core were constructed and tested. We also developed a method for analytical calculation of the optimal air gap of magnetic core necessary for maximizing stored energy, where we used power approximation of the *B*–*H* curve of the ferromagnetic material. This method is valid for the calculation of the dependence of the stored energy on the value of air gap of the core. One of these models was used as an example of stored energy calculations. The experimental stored energy values are close to the calculated values.

Keywords: Superconducting magnetic energy storage; Magnetic core; Stored energy computation; High-temperature superconductors

1. Introduction

SMES is one of the most attractive power applications of superconductors that already exists in the market. Those SMES's are used for improving the power quality and stabilizing the grid [1]. The major elements of these SMES's are Nb–Ti coils immersed in liquid helium bath. But HT-SMES's presently pass through the first stage of research and development [2–7]. This process already encountered several difficulties related to their electromagnetic and thermal properties. Traditional cryogenic design of HT-SMES's lies in cooling down the HTS coil to 20–30 K by cryocooler. However charge and discharge of the coil generates heat evolution that leads to thermal instability of the system [2,3]. We overcome this difficulty by immersing the HTS coil into liquid nitrogen bath in temperature interval 64–77 K [4,5]. But this comparatively high temperature leads to reduction of critical current with simultaneous decrease of maximal magnetic flux density in the coil which, in turn, brings decrease of the stored energy.

Refs. [8,9] considered an idea to increase stored energy by introducing a magnetic core into SMES. The magnetic core not only increases the maximal flux density but also, being properly designed, decreases magnetic field on the winding. Hence in design of the magnetic core for SMES one has to achieve two main goals: (1) a choice of the optimal air gap length which maximizes stored energy for given characteristics (size and number of Ampere-turns) of the coil and (2) minimization (at a given gap length) magnetic field on the winding varying the core's form. The analytical method of optimization of the core parameters is preferable because it permits to find a best combination of the core and coil parameters. In the present work we describe an analytical method for calculating the stored energy of the superconducting coil surrounded by iron core. The known analytical methods of optimization an air-gapped core are concentrated on electrical performances of reactor not including a maximal stored energy [10]. Our method allows calculating the stored energy of SMES including an HTS coil with an iron core for given parameters of the coil: the inner diameter and the Ampere-turns number. Our SMES model was used as an example of stored energy calculations. The stored energy values obtained in experiments coincide with the calculated values. We discuss also the feasibility of 1 MJ class SMES including iron core.

* Corresponding author. Tel.: +972 3 531 8607; fax: +972 3 535 3298.
E-mail address: freidma@mail.biu.ac.il (A. Friedman).

0924-0136/$ – see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.jmatprotec.2004.07.005

2. Calculation of the energy stored in a coil with iron core

Among many forms of a core we choose 'pot-core' configuration (Fig. 1) because it has an axis of symmetry shared by the coil and, presumably, provides the minimal volume of the core $V_{st} = l_{st}A$ (where l_{st} is an average length of the core and A is an area of its cross-section). Moreover the traditional U-shape and E-shape cores cannot reduce the magnetic field on the winding because they do not embrace the entire coil. The core consists of six sections with different directions of the lamination that coincide with the main direction of the magnetic field in each section.

To optimize design of the magnetic core we have to define the optimal length of air gap. The main point of the used method is clear from Fig. 2. Further we assume that magnetic flux density has the same value B ($B = B_g = B_{st}$) in the entire magnetic circuit and also that the cross-section of the gap is equal to the cross-section of the core. With this assumption the energy density is constant over the volume of the core. Fig. 2 shows straight lines, which display Ampere's law (taking $H_g = B/\mu_0$):

$$H_{st}l_{st} + \frac{Bl_g}{\mu_0} = \mathrm{IN} \quad (1)$$

for the different gap lengths l_g, where $\mu_0 = 4\pi \times 10^{-7}$ H/m is permeability of vacuum.

We approximate the B–H curve of the magnetic material by a power law:

$$H_{st} = \alpha B^n \quad (2)$$

Substitution of Eq. (2) into Eq. (1) gives the one-to-one correspondence between the length of the gap l_g and B for our magnetic circuit

$$l_g = \mu_0 \left(\frac{\mathrm{IN}}{B} - l_{st}\alpha B^{n-1} \right) \quad (3)$$

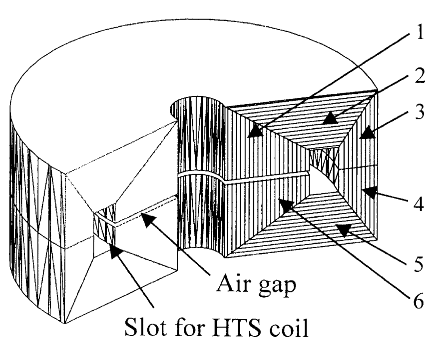

Fig. 1. The magnetic core made of laminated steel in the form of "pot-core". Core consists of six sections. Hatchings show the lamination direction in each section.

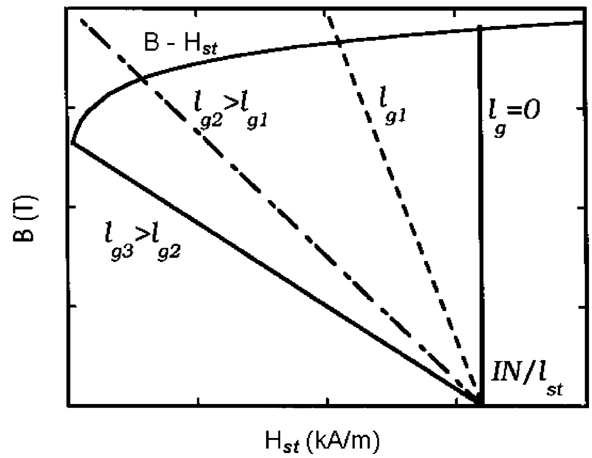

Fig. 2. Illustration of the method of the calculation of the optimal air gap for maximizing the stored energy in the coil with magnetic core.

The stored energy W can be represented in two ways: in terms of the coil's current or in terms of the magnetic field

$$W = \int_V \left(\int_0^B H \, \mathrm{d}B \right) \mathrm{d}V \quad (4)$$

where H and B are the local values of the magnetic field strength and magnetic flux density, respectively. In the core, H and B are related by the B–H curve of the core's material.

We can substitute outer integration over the entire volume in Eq. (4) by the sum of energies stored in the core and in the gap each of them being multiplication of the energy density on the volume

$$W = W_g + W_{st} = l_g A \int_0^B H_g \, \mathrm{d}B + l_{st} A \int_0^B H_{st} \, \mathrm{d}B \quad (5)$$

Substituting Eqs. (2) and (3) into Eq. (5) we find the stored energy of the coil W with core as the sum of energies in the air gap W_g and in the core W_{st}:

$$W_g = \tfrac{1}{2} B H_g A l_g = \tfrac{1}{2} A \,\mathrm{IN}\, B - \tfrac{1}{2} A l_{st} \alpha B^{n+1} \quad (6)$$

$$W_{st} = l_{st} A \int_0^B \alpha B^n \, \mathrm{d}B = \frac{\alpha}{n+1} B^{n+1} A l_{st} \quad (7)$$

The total energy is then

$$W = \frac{1}{2} A \,\mathrm{IN}\, B - \frac{n-1}{2(n+1)} A l_{st} \alpha B^{n+1} \quad (8)$$

Eq. (8) defines W is a function of only one variable, B. We can find an optimal value of B from the condition $\mathrm{d}W/\mathrm{d}B = 0$

$$\frac{\mathrm{d}W}{\mathrm{d}B} = \frac{1}{2} A \,\mathrm{IN} - \frac{n-1}{2} A l_{st} \alpha B^n = 0 \quad (9)$$

Solving this equation we define the optimal value B_{opt} as

$$B_{\mathrm{opt}} = \left[\frac{\mathrm{IN}}{\alpha(n-1)l_{\mathrm{st}}}\right]^{1/n} \quad (10)$$

Substituting this value into Eqs. (3) and (8) we calculate the optimal air gap and the maximal stored energy:

$$l_{\mathrm{g(opt)}} = \frac{n-2}{n-1}\frac{\mu_0\,\mathrm{IN}}{B_{\mathrm{opt}}} \quad (11)$$

$$W_{\max} = \frac{n}{2(n+1)}\,\mathrm{IN}(AB_{\mathrm{opt}}) \quad (12)$$

3. Example of SMES

The major elements of our SMES's are BSCCO coils purchased from American Superconductor Corp. at 1995 and 1998. The parameters of the coils are given in Table 1. In the first SMES [4] the magnetic core is made of 12 pairs of C-cores and its cross-section fill only about 40% of the possible area of the core. In the second SMES [5] the magnetic core has maximal possible cross-section A as shown in Fig. 1. A clearance between the coil and the core is necessary for reducing magnetic field on the winding (see below). Both SMES devices were successfully tested in liquid nitrogen at temperatures of 77 K and 64 K. Results of these tests are given in [4] and [5]. The stored energy values found at the tests are close to the calculated values.

Below we give an example of calculation optimal air gap in the core of our second SMES model.

For the isotropic steel that have been used in our SMES (Stabolec, grade 250-30A) the B–H_{st} dependence is approximated by

$$H_{\mathrm{st}} = 7.4B^{12} \quad (13)$$

Table 1
Parameters of two laboratory SMES models

Parameters	SMES-1		SMES-2	
HTS coil				
Outside diameter (mm)	246		390	
Inside diameter (mm)	194		370	
Height (mm)	18		62	
No. of double pancakes	3		8	
No. of turns	240		256	
Conductor length (m)	160		300	
Inductance (H)	0.017		0.04	
Operating voltage (V)	15		400	
Operating temperature (K)	64	77	64	77
Critical current (A)	49	22.2	110	55
Peak power (kW)	0.73	0.33	44	22
Maximal stored energy (J)	20.4	4.2	240	60
Ferromagnetic core				
Outside diameter (mm)	315		530	
Height (mm)	100		250	
Cross-section area (m^2)	0.013		0.08	
Mass (kg)	20		430	
Length of air gap (mm)	8	4	10	19
Coil with core				
Maximal stored energy (J)	122	52	1500	750
Energy gain	6	12.4	6.2	12.5
Average inductance (H)	0.1	0.21	0.25	0.5

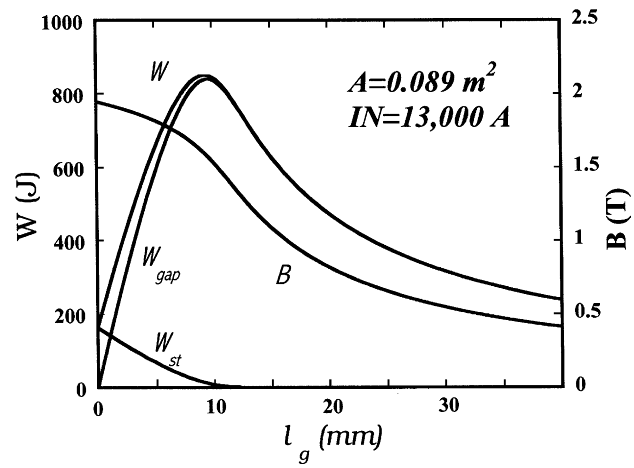

Fig. 3. Dependencies of the stored energy in the gap, in the core, the total stored energy and optimal magnetic flux density on the air gap length for our SMES model.

Now we substitute Eq. (13) and the parameters of the coil (Table 1) into Eqs. (3), (6)–(8) and plot graphs of stored energy in the gap, in the core, total stored energy and B versus l_{g} (Fig. 3). One can see that there is a fast increase of the stored energy with introducing an air gap into the magnetic circuit. The maximal stored energy of about 850 J is achieved at $l_{\mathrm{g}} \cong 0.9$ cm.

Further increase of the gap causes a drop of the stored energy. The small (~10%) deviation from optimal value of the gap has a negligible influence on the stored energy but out of this interval there is a fast drop of the stored energy. It is important to note that the optimal value of magnetic flux density is about 1.6 T, i.e. far from saturation.

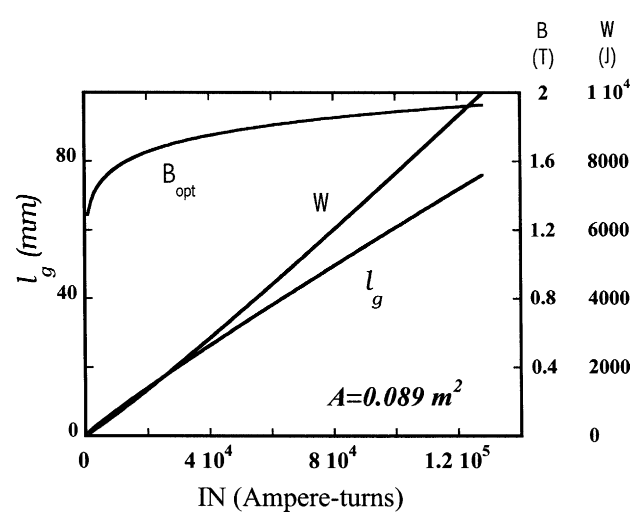

Fig. 4. Dependencies of the maximal stored energy and optimal values of the magnetic flux density and air gap length on the number of Ampere-turns for our SMES model.

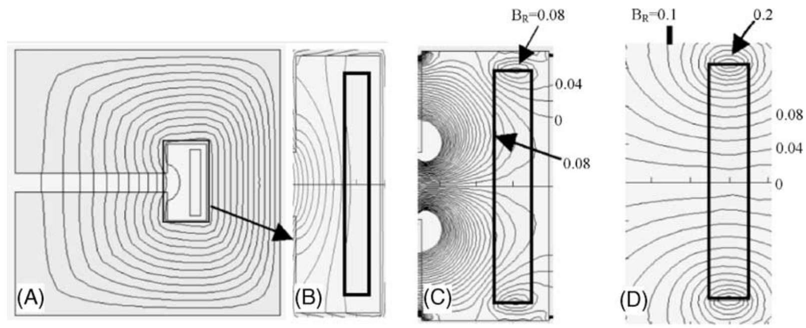

Fig. 5. Magnetic field lines in the coil with core shown in Fig. 1 (A) and in the slot around HTS coil (B). Distribution of the radial component of magnetic field on the coil with (C) and without (D) magnetic core.

When the current of the coil increases as, for example, with decreasing of the temperature, the gap has to be increased to optimal value corresponding to the number of Ampere-turns. Fig. 4 shows the dependences of the optimal values of B and l_g and maximal stored energy on the number of Ampere-turns. We see almost linear increase of the stored energy and the gap with increase of the number of Ampere-turns. Such dependence is different from the coil without core, which shows a square-law dependence of the stored energy on the number of Ampere-turns. The experimental data (Table 1) are close to calculated stored energy values. We received with coil made of 600 m wire (doubled wire was used) the stored energy that can be received without core with 5 km of HTS wire [7].

4. Detailed design of the core

The form of the slot where HTS coil is placed has to be optimized to minimize degradation of the critical current (I_C) of the coil caused by the magnetic field. I_C of the BSCCO tape depends on the flux density of the magnetic field and on its direction. The field perpendicular to the broad side of the tape (radial component of the field B_r) causes maximal degradation of the I_C. We optimize the form of the slot by minimizing only this component of the magnetic field on the winding. The calculations were carried out with FEA software PC-OPERA.[1] Fig. 5A and B shows the magnetic field lines in the magnetic core with gap. Most part of the magnetic flux is concentrated in the core. The distribution of the radial component B_r of the magnetic flux in the cross-section of the coil with magnetic core and without it is shown in Fig. 5C. The maximal value of B_r is on the top and bottom surfaces of the coil without core. In the coil with core there are two other zones of high radial field on the inner surface related to dissipation fields of the core's gap. Small distances between the top and bottom surfaces of the coil and the core help to decrease B_r in this zone. The distance between inner surface of the coil and core has to be optimized to ensure the maximal B_r on this surface equal to the B_r value on the top and bottom surfaces. This way we succeeded to receive a maximal value of B_r less than 50% of B_r on the coil without core.

The dissipation fields around the gap strongly increase with increasing the gap length. Our design permits to decrease the length of the main gap by introducing small gaps between all six parts of the core with total gap length as calculated. In the systems with big stored energy and proportionally big gap the parts 1 and 6 of the core can be divided on several parts with gaps between them. Another way to decrease the gap is using powdered core with high saturated flux density and low permeability. In this case one can calculate the optimal air gap by the method of Section 2 with using a suitable B–H curve approximation. Only length of the parts with low permeability has to be taken into account neglecting the reluctance of the parts made of laminated steel.

5. Enlargement of SMES with magnetic core

For a further increase of stored energy it is necessary to increase the cross-section of the core. Fig. 6 shows stored

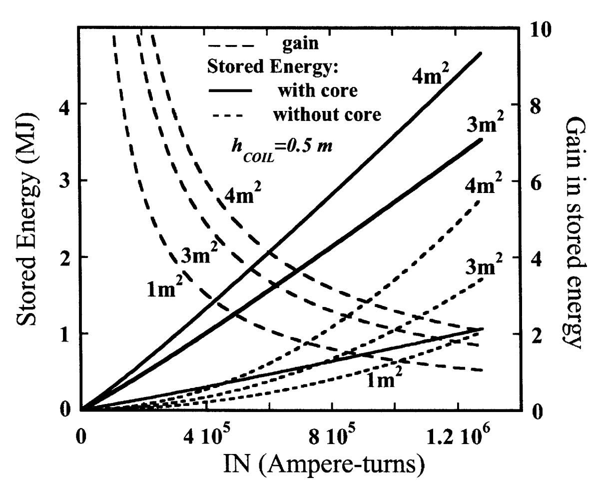

Fig. 6. Dependencies of the stored energy and the gain in the stored energy on the number of Ampere-turns at different cross-sections of the magnetic core.

[1] Vector Fields Ltd., UK.

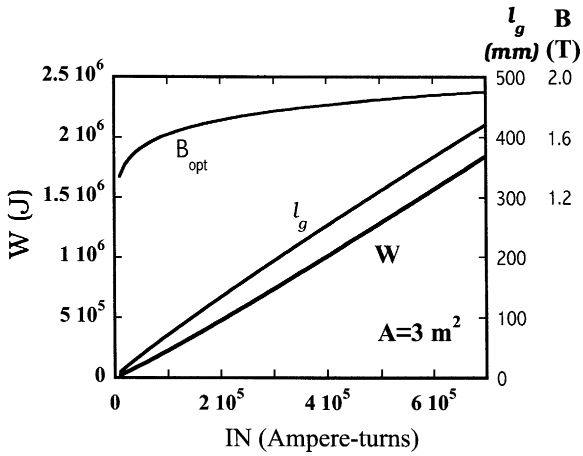

Fig. 7. Dependencies of the maximal stored energy and optimal values of the magnetic flux density and air gap length on the number of Ampere-turns for MJ-class SMES.

energy of the coils with and without cores with different cross-sections: 1, 3, and 4 m^2. For the last two cores the stored energy of 1 MJ can be achieved at reasonable numbers of the Ampere-turns of the coil. Fig. 6 also shows a gain in the stored energy. One can see that for the SMES with the stored energy about 1 MJ the gain is of 5–8. The stored energy, optimal gap and optimal magnetic flux density for the SMES with core cross-section 3 m^2 are shown in Fig. 7. From Figs. 6 and 7 we can find the necessary parameters of the coil and the magnetic core for designing, for example, SMES having the stored energy of 1 MJ. In principle such SMES can be built using the coil made of modern BSCCO wire. Indeed such core will have a huge mass. An estimation the volume of the 'pot-core' gives us $V = 3Ar$, where r is the radius of the cross-section of the core. For $A = 3\,m^2$ the volume and the mass of the core are about 9 m^3 and 70 t that is close to mass of a big grid transformer. We can conclude that use of a magnetic core is limited by comparatively low level of stored energy. Increase of the current carrying capacity of the HTS wires will allow reducing the diameter and the mass of the core.

6. Conclusion

Introducing a magnetic core into SMES is the effective mean of increase its stored energy. Two laboratory scale SMES's were constructed with adjustable able air gap that allows to maximize stored energy for every critical current of the coil (depending on the temperature). The method for analytical calculation of the optimal air gap of magnetic core necessary for maximizing stored energy was developed. The proper design of the core noticeably reduce magnetic field on the winding.

Acknowledgement

This research has been supported by the Israel Ministry of National Infrastructures.

References

[1] W. Buckles, W.V. Hassenzhal, IEEE Power Eng. Rev. 20 (2000) 16.
[2] S.S. Kalsi, D. Aized, B. Conner, G. Snitchier, J. Campbell, R.E. Schwall, J. Kellers, T. Stephanblome, A. Tromm, P. Winn, IEEE Trans. Appl. Supercond. 7 (1997) 971.
[3] R. Mikkonen, J. Lehtonen, J. Paasi, Applied superconductivity 1999, in: Proceedings of the EUCAS 1999, vol. 1, IOP Publishers, Bristol, UK, 2000, p. 1175.
[4] A. Friedman, N. Shaked, E. Perel, M. Sinvani, Y. Wolfus, Y. Yeshurun, Cryogenics 39 (1999) 53.
[5] A. Friedman, N. Shaked, E. Perel, M. Sinvani, Y. Wolfus, Y. Yeshurun, IEEE Trans. Appl. Supercond. 13 (2003) 1875.
[6] R. Kreutz, H. Salbert, D. Krischel, A. Hobl, C. Radermacher, N. Blacha, P. Behrens, K. Dutch, IEEE Trans. Appl. Supercond. 13 (2003) 1860.
[7] J. Pitel, P. Kovac, J. Lehtonen, J. Paasi, Supercond. Sci. Technol. 14 (2001) 173.
[8] T.Y.T. Morisue, J. Appl. Phys. 75 (1994) 6969.
[9] Y.S. Cha, J. Appl. Phys. 73 (1993) 6787.
[10] T.G. Wilson Jr., T.G. Wilson, H.A. Owen Jr., IEEE Trans. Power Electron. 13 (1998) 3.