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STUDY ON IMPACT OF HTS WINDING CONFIGURATION ON ENERGY VALUE AND MAGNETIC FIELD DISTRIBUTION IN SMES

ABSTRACT *The article describes a physical model of Superconducting Magnetic Energy Storage System (SMES) built in the Laboratory of Superconducting Technology in the Electrotechnical Institute. The considered problem concerns the choice of the superconducting winding configuration, which can be responsible for the required energy value in a limited space of the strong magnetic field. Possible configurations of the windings were analysed with particular focus on the solenoid and the toroidal configuration. The results of the calculations of the magnetic field distribution and the energy accumulated in the coil for the considered shield configuration have been described. It was shown that for the tested SMES model with energy of 34 kJ at temperature 13 K, it is possible to use such magnetic field shielding configuration, which allows to limit the magnetic field zone with an intensity exceeding the limit values and energy increase by 14%.*

Keywords: *SMES, magnetic shielding, magnetic field distribution*
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1. INTRODUCTION

Electrical power generation is changing dramatically across the world because of the need to reduce greenhouse gas emissions and to introduce renewable sources. The power network faces great challenges in transmission and distribution to meet demand. The introduction of many renewable energy sources into the energy system causes a number of problems. One of them is the unstable quality of energy supplies from these sources, due to the unpredictability of the output power, e.g. from a wind farm or a solar farm due to changing weather conditions. One solution is to store electricity and use it at a time when there is a demand.

Electricity is easily transformed into other types of energy such as heat, light, motion, chemical energy, but it is very difficult to store. Small energies are stored in the electrical and magnetic fields.

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The discovery of superconductivity in 1911 enabled the construction of windings for magnets with high induction in large spaces without power losses. The windings for storage systems are wound with low temperature superconducting (LTS): NbTi-Cu and Nb_3Sn composite wires (from 1960) and high temperature superconducting (HTS) BSCCO and YBCO matrix tapes (from 1986). The first SMES (Superconducting Magnetic Energy Storage) were designed to storage the energy of at least 5,000 MWh using solenoid coils with a diameter of 1 km. Currently SMES are built as auxiliary devices to protect receivers sensitive to voltage fluctuations, to improve the reliability and the quality of an energy supply.

Compared to other energy storage systems, the SMES (superconducting magnetic energy storage device) are characterized by high efficiency (up to 95%) due to the absence of resistive losses. They also have a short response time due to the operation based only on electromagnetic transformations of electricity without the use of other types of energy. SMES are characterized by long life (up to 30 years), are environmentally friendly and reliable due to the moving parts absence. Superconducting energy storage can be important in the development and modernization of the grid infrastructure. Due to the speed of operating, SMES can act as a protecting element against the effects of short-circuits and voltage fluctuations [1].

2. THE IDEA AND THE MODEL OF SMES DEVICE

The operation of the superconducting energy store is associated with the phenomena that do not exist in conventional energy storage devices. This is due to the specific features of superconducting materials that conduct electricity without resistive losses in the superconducting state. The SMES concept is based on the presence of a magnetic field as a result of the DC current in the winding and the ability to store energy *E* in pure form in the generated magnetic field [1].

Functionally, SMES differs from other energy storage technologies in that the only conversion process is to convert alternating (AC) into constant (DC) current and vice versa. As a result, there are no thermodynamic losses associated with the conversion of one type of the energy to another. The energy of the magnetic field can be expressed by dependence [2]:

$$E = \frac{1}{2} V \mu H^2 = \frac{1}{2} V \frac{B^2}{\mu} \tag{1}$$

where:

H – magnetic field strength,
B – magnetic field induction,
V – volume of the magnetic field,
μ – magnetic permeability.

The superconducting energy storage system consists of three basic elements: superconducting winding, power conditioner (PCS system) and cooling system.

These elements are extended with a control system, a power supply and protection system (e.g. a system for detecting an uncontrolled superconductor transition to a resistive state called a quench detector) (Fig. 1).

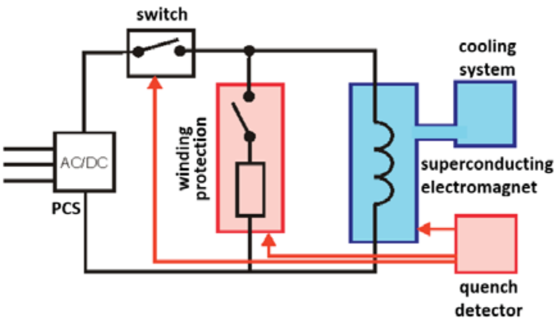


Fig. 1. Structure of SMES system

Due to the DC current in the superconducting winding, a voltage conversion system called a Power Conditioning System (PCS) or a power conditioner is required [3]. The PCS system (e.g. AC / DC converter) electrically connects the power grid with the SMES or the receiver or is integrated with a renewable energy source such as a wind power plant. An equally important element of the system is the control and regulation system, which function is to protect the entire system against the occurrence of transient states in a superconductor electromagnet. Selection of an auxiliary system parameters affects the total cost of construction and operation of the energy storage.

Unlike emergency battery systems, in which the converter system or capacitor systems are the most expensive, in which the most expensive are the capacitors, the cost of components of the superconducting reservoirs are distributed evenly between the electromagnet, the cooling system and the converter system.

The electromagnets used in the SMES devices most often have solenoidal configuration but it is not the only possible configuration. The practical application of SMES entails an issue of efficiency, but also a nearby exposure to large magnetic fields. Recent projects in the world focused on the toroidal configuration for SMES (Fig. 2).

a) b)

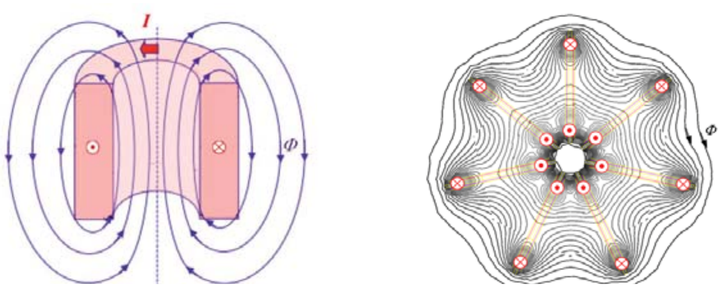


Fig. 2. Magnetic field lines Φ generated in winding:
a) solenoidal and b) toroidal configuration [4, 5]

There is a strong magnetic field for the solenoid winding in a large area around the winding, which causes the intensity of the field surrounded by SMES with high energy values exceeds the values allowed by standards and is dangerous for users. The advantages of a simple structure and smaller sizes of the solenoid winding are compensated by the adverse effect of the magnetic field on the environment. In the coil systems or toroids, significant forces act on individual component coils, which must be balanced using structural elements [6, 7]. The distribution of these forces depends on the geometry and shape of the windings.

To limit the strong magnetic field outside the winding, large SMES devices are now more often designed in a toroidal configuration. However, the energy densities obtained in this configuration are smaller than in the solenoid system. The developed constructions are the result of a compromise between the need to obtain maximum energy and the necessity to limit the impact of the magnetic field on the environment.

The superconducting electromagnet for the SMES model was designed and built in the Lublin Laboratory of Superconducting Technology in the Electrotechnical Institute, in cooperation with the Lublin University of Technology as part of the research project entitled "A SMES device with high-temperature electromagnet and autonomous cooling system [8–11]. HTS winding was made of composite tape AMSC Bi-2223 HTS Strength Wire from American Superconductor Inc. The seven double coils, in which the windings are wound in opposite directions, are placed on a common bobbin (Tab. 1).

TABLE 1
The parameters of SMES magnet

Parameters	**Values**
Number of pancakes	14
The number of turns in a pancake	140
Number of magnet turns of the magnet	1960
Outer radius of the magnet	0.312 m
Magnet height	0.194 m
Length of HTS tape	1500 m
HTS tape for winding	
AMSC HTS HS Wire SSL Bi-2223 ($Bi_2Sr_2Ca_2Cu_3O_{10}$)	
Thickness /width	0.31/4.20 mm
Critical current / 77 K	115 ÷ 128 A

The electromagnet operates in a superconducting state at a cryogenic temperature below 77 K in a cryostat with 7×10^{-6} Pa vacuum insulation. In order to improve the conditions of a heat dissipation to the cooling head, a radiation screen was placed inside the cryostat (Fig. 3), [9].

The value of the operating current in the electromagnet must be lower than the lowest value of the critical current of the belt used among all 14 windings. Decreasing the HTS winding operating temperature increases the critical current value.

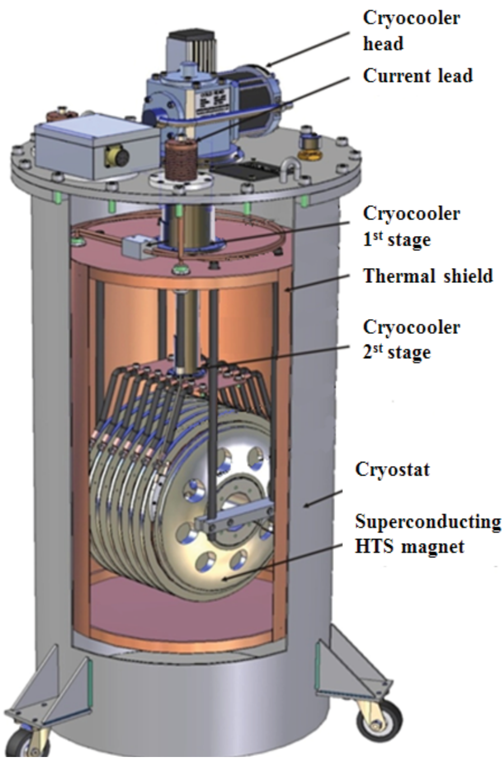


Fig. 3. Project of HTS SMES magnet in cryostat [9, 10]

The superconducting winding for SMES has been experimentally tested under cryogenic conditions for a current in the winding from 25 to 264 A and a temperature of 77 to 13 K.

3. THE MAGNETIC FIELD AND THE ENERGY OF SMES DEPENDING ON THE CONFIGURATION OF THE SUPERCONDUCTING ELECTROMAGNET

Numerical calculations of the magnetic field distribution generated by the electromagnet were executed using CEDRAT's FLUX® software based on the MES method. The distributions of magnetic field induction generated by the electromagnet for different values of the current in the coil shown in Figure 4.

The maximum values of magnetic induction and energy are summarized in Table 2. The energy of the magnetic field increases more than 110 times from 0.216 kJ to 24.051 kJ with the maximum magnetic induction changes from 0.237 T to 2.5 T by increasing the current value in the winding by more than ten times from 25 A to the maximum value of 264 A.

TABLE 2
Values of energy and magnetic induction as a function of operating current *I* (calculation results)

Operating current, *I*, A	**25**	**50**	**100**	**150**	**180**	**200**	**220**	**240**	**264**
Energy *E*, kJ	0.216	0.863	3.451	7.764	11.180	13.803	16.702	19.877	24.051
Magnetic induction B_{max}, T	0.237	0.474	0.948	1.420	1.710	1.900	2.090	2.280	2.500
Temperature *T*, K	77	60	→		35	→			13

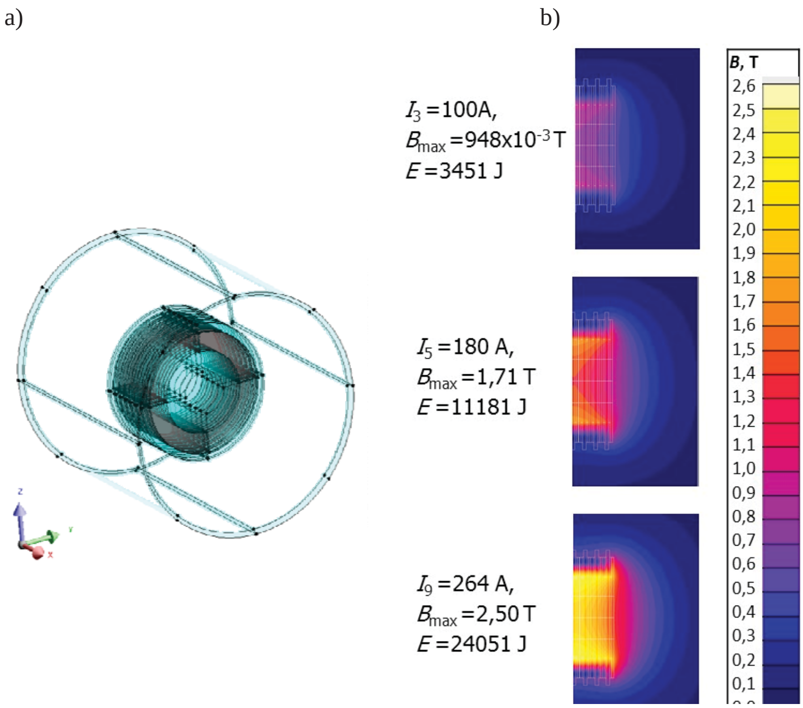


Fig. 4. Superconducting coil in solenoid configuration:
a) the geometry b) the distribution of the magnetic induction

The influence of the superconducting winding configuration on the magnetic field distribution and energy values was demonstrated on the basis of calculations made for the electromagnet model in the toroidal arrangement [12]. The electromagnet was made of 7 identical double coils as in the solenoid, but prepared in the arrangement shown in Figure 5a. The simulations were performed for three current values in the electromagnet 25 A, 180 A and 264 A (Fig. 5b.)

In the toroidal configuration, the value of magnetic induction and the energy of the generated magnetic field depends on the radius of the toroid. When the coils are symmetrically moved away from the axis of the toroid, the induction and the energy values are reduced. At the same value of the toroid radius, the induction and the energy of the magnetic field increases as the current in the winding increases.

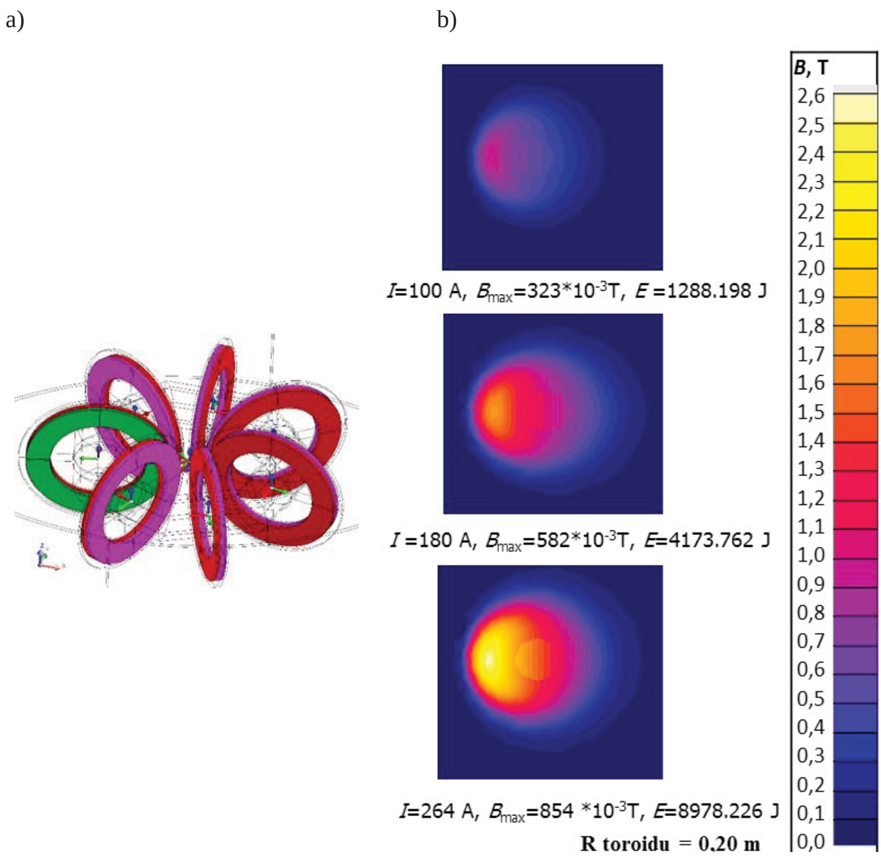


Fig. 5. Superconducting coil in toroid configuration:
a) the geometry b) the distribution of the magnetic induction

TABLE 3
Values of energy and magnetic induction for the coil in solenoidal and toroidal configurations

Operating current *I*, A	**Energy *E*, kJ**		**Magnetic induction B_{max}, T**	
	Solenoid	Toroid	Solenoid	Toroid (R = 0.2 m)
25	0.216	0.081	0.237	0.081
100	3.451	1.288	0.948	0.323
180	11.180	4.174	1.710	0.582
264	24.051	8.978	2.500	0.854

The solenoidal configuration is more effective when it comes to storing energy in a winding made of the same superconductor wire mass [13]. For the same value of current in the winding I = 100 A, the energy in the solenoid is 2.6 times higher than in the best considered toroidal configuration with a radius of 0.20 m.

4. INCREASING THE ENERGY AND DECREASING THE HIGH MAGNETIC FIELD OUTSIDE THE SMES`

The aim of SMES design is to achieve the highest possible value of a stored energy. The development of the superconducting wire technology and cooling techniques results in greater energy storage capacity for the same superconductor mass. At the same time the intensity of the magnetic field generated outside the devices are therefore also increasing. The construction of SMES systems with the largest energies has been abandoned while remaining at the construction of micro-SMES, but the issue of the magnetic field effect on the environment is still very important.

According to Polish standards, the permissible component of the electromagnetic field in the form of magnetic field strength H is 2.5 kA/m. This value is defined as the acceptable safe value for humans [14, 15]. Using the numerical analysis, the intensity of the magnetic field generated outside the SMES was examined. A method of limiting of the strong magnetic field area and the value of its intensity without decreasing the efficiency of energy storage has been proposed.

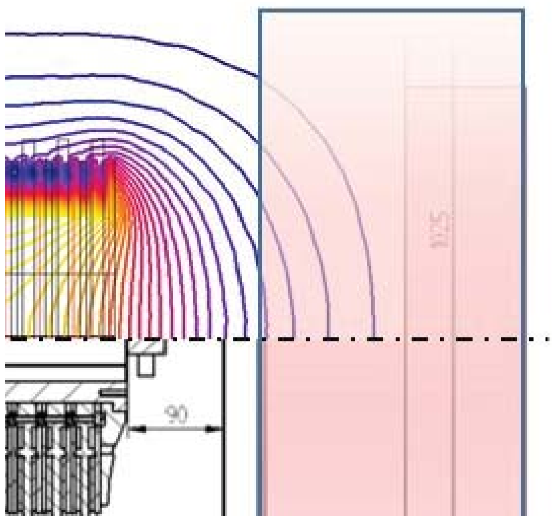


Fig. 6. Cross section of cryostat with HTS magnet and magnetic field induction distribution

In the model of SMES built in a Laboratory of Superconducting Technology in Electrotechnical Institute, the HTS electromagnet is placed transversely in the cryostat (Fig. 6) and it generates the highest intensity magnetic field along the winding axis outside the cryostat also. The maximum value of the magnetic field intensity generated by the winding is 1.99 × 103 kA/m at the current 264 A (Fig. 7).

The intensity of the magnetic field decreases with the distance from the centre of the electromagnet and at the external wall of the cryostat it is 230 kA/m. This value exceeds the permissible magnetic field value, i.e. 2.5 kA/m. The intensity of the field decreases to values below 40 kA/m at a distance of 0.25 m from the cryostat wall, exceeding nearly twice the permissible values.

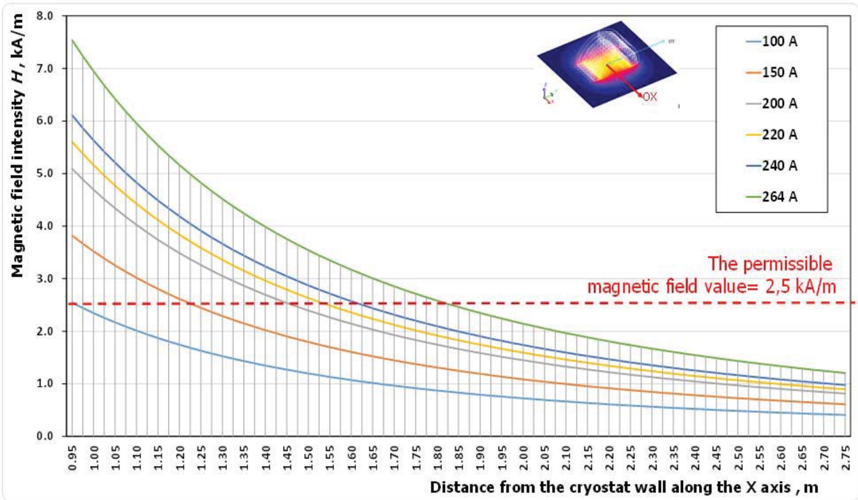


Fig. 7. Magnetic field intensity *H*, kA/m, along OX axis

The distribution of the magnetic field strength *H*, kA/m, for the current *I* = 264 A along the axis of the winding as a function of the distance from the centre of the electromagnet is shown in Figure 8.

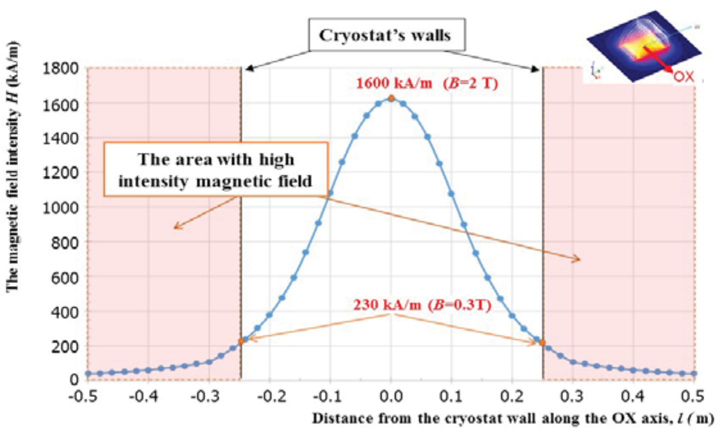


Fig. 8. Magnetic field intensity *H*, A/m distribution, for operating current *I* = 264 A as a function of the distance from the centre along the magnet axis

Considering that the tested physical model of SMES is a device with small dimensions and energy, we can expect much higher magnetic field values in larger scale devices (GJ energies). It is advisable to shield the field outside the device in order to reduce its impact on people and devices in its surroundings.

4.1. Method to reduce strong magnetic field around model of SMES

In order to limit the magnetic field operation space of a dangerous intensity for the environment while maintaining the storage energy efficiency, it was proposed to use shielding, ferromagnetic elements that improve the magnetic field distribution generated in the superconducting winding. For the construction of shielding elements were electrical sheets applied. The arrangement of the ferromagnetic elements was selected for use in the existing physical model of the HTS magnet. The cross-sectional view of the model shown in Figure 9. The elements of the tubular screen are marked in green, while the disc elements and rings are blue.

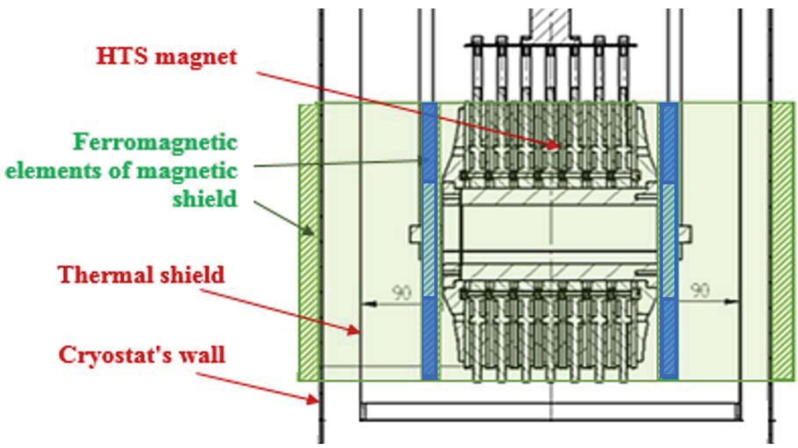
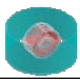
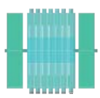


Fig. 9. Arrangement of shielding elements – cross section of electromagnet in the cryostat

For each configuration of the shielding elements shown in Figure 9, calculations of magnetic field distribution, maximum values of magnetic induction and magnetic field energy were carried out. The most important results are summarized in Table 4.

The obtained results were compared to the results obtained earlier for the winding in the "0" configuration. The ferromagnetic elements cause the field strength values to change.

TABLE 4
Values of magnetic induction and energy obtained from numerical calculations for six considered configurations of ferromagnetic elements

No.	Configuraction			*I*, A	B_{max}, T	*E*, kJ
0.		Winding without shielding elements		180	1.70	11.180
				264	2.50	24.051
1.		Winding with single shielding ring		180	2.47	11.268
				264	2.85	24.003
2.		Winding with single shielding disc		180	1.73	11.444
				264	2.52	24.176
3.		Winding with a tubular shield around the cryostat		180	1.73	11.421
				264	2.54	24.569
4.		Winding with a partial tubular shield around the cryostat t		180	1.71	11.182
				264	2.50	24.052
5.		Winding with two shielding discs	gr. 0.02 m	180	1.08	11.955
				264	2.53	24.949
			gr. 0.04 m	180	1.89	12.466
				264	2.60	26.477
			gr. 0.06 m	180	2.01	12.715
				264	2.63	27.278

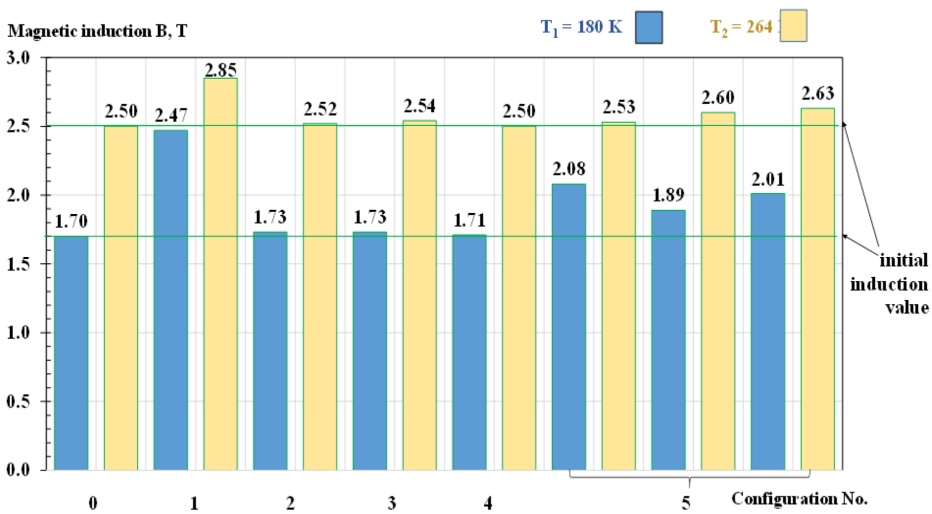


Fig. 10. Values of magnetic induction *B* for selected shielding configurations

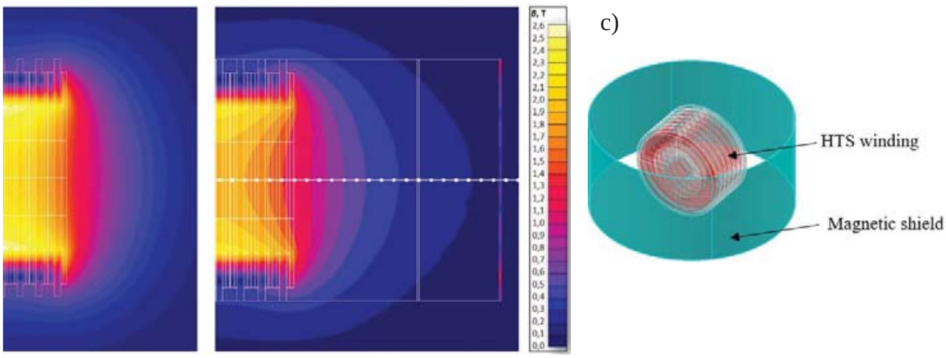


Fig. 11. Configuration with tubular shield that is optimal for field limitation – distribution of magnetic induction *B* in the system a) without shielding elements, b) with tubular shield, c) arrangement of elements, I = 264 A

A tubular shield reduces the field intensity to limit values – 2.5 kA/m for the tube thickness of 120 mm in approx. 0.22 m from the cryostat, and the reduction in the distance of 0.32 m for a shield with a thickness of 40 mm (Fig. 11). Increasing the thickness of the shield enhances its effects.

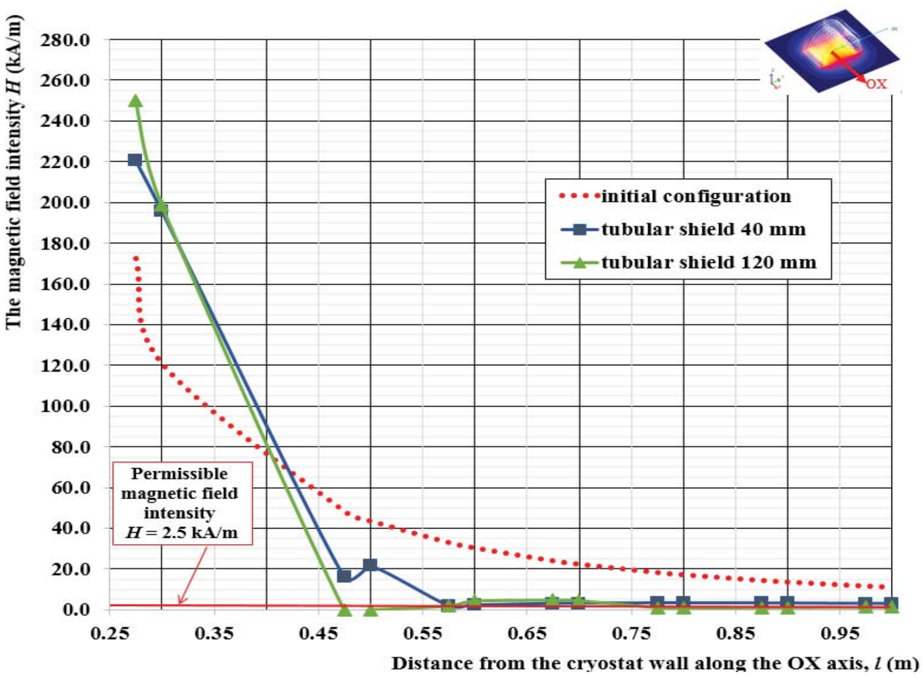


Fig. 12. Magnetic field intensity *H* for tubular shield configuration for two shield thicknesses, *I* = 264 A

The second promising solution is the configuration with two shielding discs placed symmetrically in the axis of the electromagnet. This solution is beneficial in terms of limiting the field intensity outside the cryostat, but with significant disc thicknesses. Figure 13 shows the interaction of 40 mm and 100 mm discs.

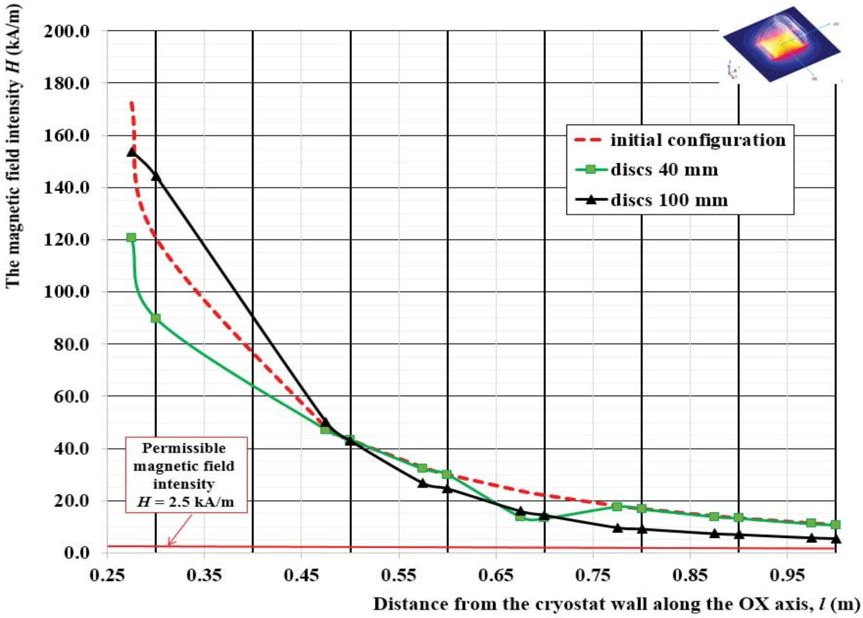


Fig. 13. Magnetic field intensity *H* for configuration of two ferromagnetic disks

Compared to a 40 mm thick tubular screen, no magnetic field restriction was observed. For a disc with a thickness of 100 mm, the value of the field strength is limited at a distance of about 0.5 m from the centre of the winding. Tubular screen with a thickness of 120 mm, limits the field to acceptable values at a distance of less than 0.5 m.

4.2. Method to increase value of energy stored in SMES model

The analysis of energy changes as a function of a current has shown that the energy values change from 0.22 kJ at 25 A to 24 kJ at 264 A. These parameters can be achieved in real conditions at temperatures of about 77 K for the smallest current and at 13 K for the maximum current 264 A. Due to the critical characteristics of the superconductor, the electromagnetic parameters of the system under a test must not exceed the critical parameters of the superconducting tape, i.e. the current density, the magnetic field intensity and the temperature. Figure 14 presents a numerically calculated energy values *E*, kJ in selected shielding configurations marked with numbers from 0 to 5 listed in Table 4. The values obtained for 180 A and 264 A currents are summarized. The largest increase of the energy values occurs for configurations no. 5.

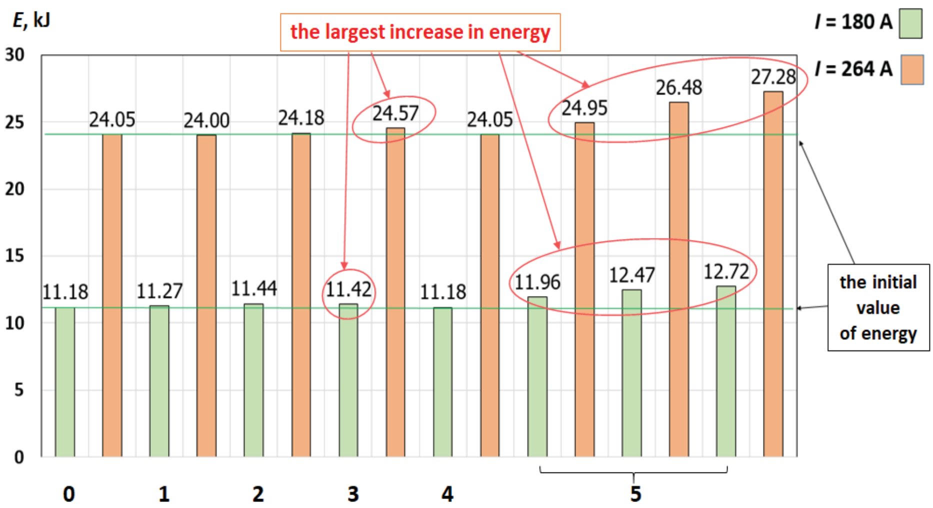


Fig. 14. Energy *E* for selected shielding configurations

The analysis of the results shows that the most advantageous configuration of the shielding elements is the arrangement of two ferromagnetic disks (Fig. 15c) placed symmetrically along the axis of the winding in the zone of the strongest magnetic field. In Figure 15a, b, the resulting magnetic induction distribution with the shield is compared to the original field distribution. The changes in the field distribution are noticeable depending on the thickness of the shielding elements and different values of the operating current in the winding.

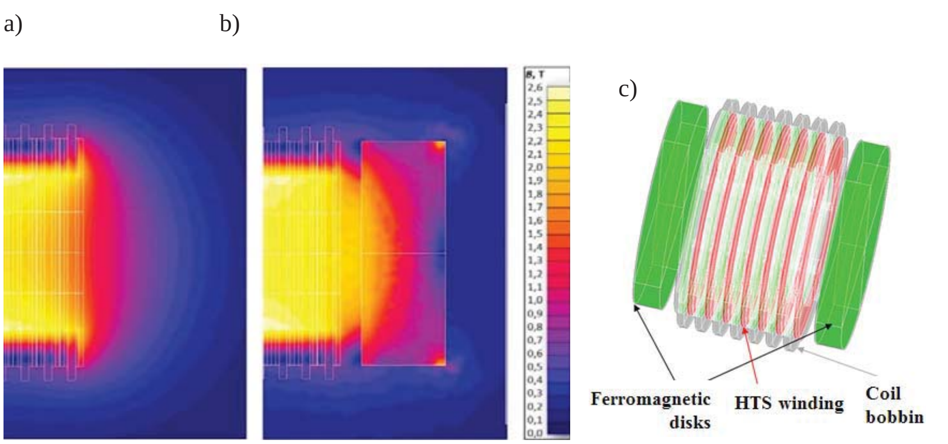


Fig. 15. Configuration with ferromagnetic disks that is optimal for the energy increasing – – distribution of magnetic induction *B* in the system a) without shielding elements, b) with a tubular shield, c) arrangement of elements, I = 264 A

The proposed configuration allows to increase the energy accumulated in the magnetic field from 4 to 13% for the maximum current in the winding 264 A and from 7 to 14% for the current 180 A according to the thickness of the discs (Fig. 16).

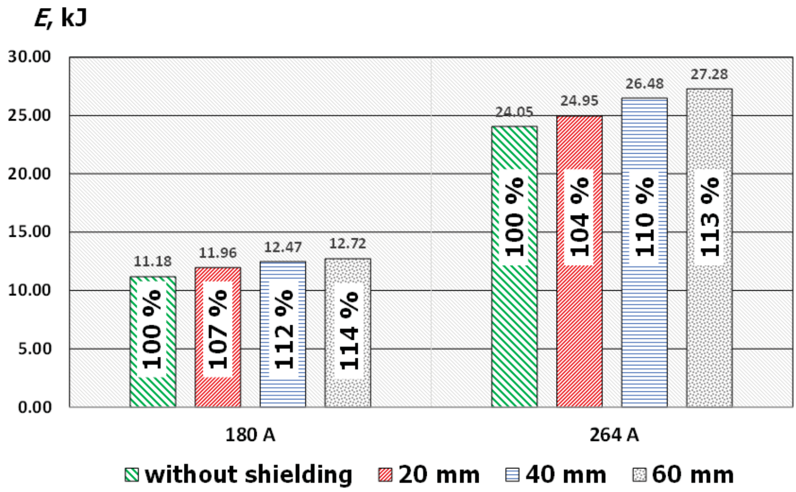


Fig. 16. Percent change in value of stored energy *E* for configuration with ferromagnetic discs

For the tested configuration, changes in the induction of the magnetic field along the axis of the electromagnet in the zone of the strongest field in the area outside the cryostat were also calculated (Fig. 17).

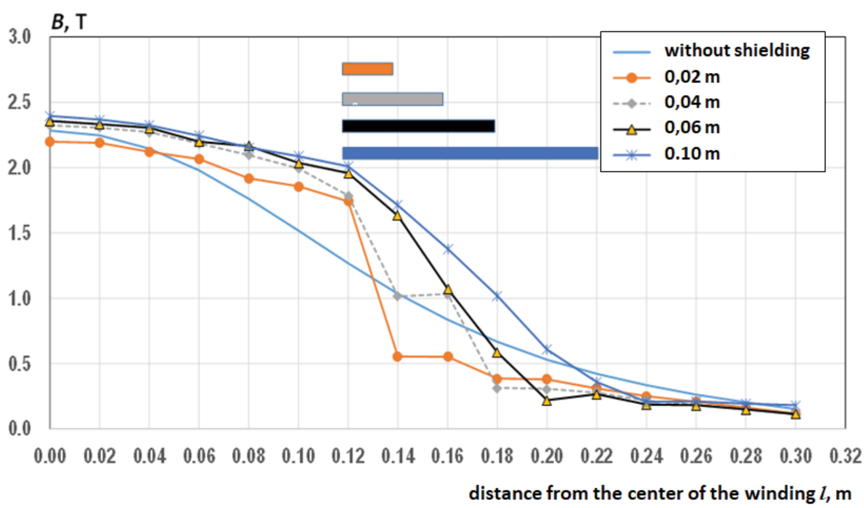


Fig. 17. Magnetic induction *B* for a configuration with ferromagnetic discs for different disc thicknesses as function of distance from winding centre *l*, *I* = 264 A

This arrangement also acts as a magnetic shielding and limits the zone of strong magnetic fields and reduces by half the value of the field intensity outside the device while increasing the value of the energy in the winding of more than ten percent.

5. CONCLUSION

The paper describes issues related to the operation of the Superconducting Magnetic Energy Storage (SMES) model, in particular the connection between the configuration of superconducting windings, the distribution of the magnetic field and the value of energy stored.

In devices where the superconducting winding is made in a solenoidal configuration, there is a problem of a strong magnetic field in a large space around the device, the intensity of which exceeds the acceptable values. In the toroidal configuration of the winding, the intensity of the magnetic field outside the winding is smaller than in the solenoid configuration. With the same length of superconducting wire, a toroidal winding constructed can accumulate energy almost three times smaller than a winding with a solenoid configuration. Obtaining comparable values of energy stored in the field requires the construction of a much larger toroid and higher costs of the superconductor and cooling of the winding.

The physical model of the HTS electromagnetic cylinder built in the Laboratory of Superconducting Technology in Lublin has been tested. The influence of the configuration on the energy at the minimum magnetic field intensity outside the device was determined. A method of shielding the winding was proposed to increase the energy value and to limit the area of strong magnetic field in the SMES environment. The numerical analysis of the magnetic field distribution in the configurations selected by the author with additional shielding elements shows that it is optimal to use discs made of electrotechnical sheet placed in the axis of the electromagnet inside the cryostat. The proposed configuration allows for an increase of 4 to 13% for the maximum operating current 264 A and 7 to 14% for the current 180 A according to the disc thickness. This configuration also can limit the zone of strong magnetic field, causing the field to be reduced to half intensity values [16]. The second preferred configuration is a tubular magnet placed outside the cryostat. This configuration slightly increases the energy, but significantly limits the field strength outside the cryostat. The 120 mm shield almost completely limits the magnetic field strength to safe values around the device. At a distance of 0.22 m, the field decreases to a permissible value of 2.5 kA/m. At a distance of 0.32 m the field archives a safe value for the tubular shield of 40 mm.

Both proposed solutions are possible to apply in the physical model of the SMES physical model located in the Laboratory in Lublin.

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BADANIA WPŁYWU KONFIGURACJI UZWOJENIA HTS NA ENERGIĘ I ROZKŁAD POLA MAGNETYCZNEGO NADPRZEWODNIKOWEGO ZASOBNIKA ENERGII

Beata KONDRATOWICZ-KUCEWICZ

STRESZCZENIE *Artykuł poświęcony jest nadprzewodnikowemu zasobnikowi energii na przykładzie modelu fizycznego zasobnika zbudowanego w Pracowni Technologii Nadprzewodnikowych Instytutu Elektrotechniki. Rozważany problem dotyczy wyboru konfiguracji uzwojenia nadprzewodnikowego, która może zapewnić wymaganą wartość energii zasobnika przy ograniczonej przestrzeni pola magnetycznego. Przeanalizowano konfiguracje uzwojeń w układzie solenoidalnym i toroidalnym. Zaproponowano metodę ekranowania pola magnetycznego badanego elektromagnesu za pomocą elementów ferromagnetycznych w kilku konfiguracjach. Przedstawiono rezultaty obliczeń metodą elementów skończonych rozkładu pola magnetycznego i gromadzonej energii w uzwojeniu dla rozpatrywanych konfiguracji ekranujących w modelu numerycznym zbudowanym w programie Flux-3D. Wykazano, że dla badanego modelu nadprzewodnikowego zasobnika o energii 34 kJ w temperaturze 13 K, możliwe jest zastosowanie konfiguracji elementów ekranujących pole magnetyczne, która pozwoli na ograniczenie strefy pola magnetycznego o natężeniu przekraczającym wartości dopuszczalne oraz zwiększenie energii zasobnika o 14%.*

Słowa kluczowe: *nadprzewodnikowy zasobnik energii SMES, ekranowanie pola magnetycznego, rozkład pola magnetycznego*

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